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Portuguese MV Underground Cable Failure Study

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Integrated Masters in Electrical and Computer Engineering
Major in Energy

Supervisor: Prof. Hélder Leite

Co-supervisor: Eng. Carina Morais

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Resumo

Esta dissertação tem como motivação melhorar o conhecimento sobre as falhas em cabos subterrâneos da rede distribuição portuguesa de MT. A compreensão dos incidentes/falhas em cabos subterrâneos é essencial para se efetuarem decisões na gestão dos ativos da rede, visto a substituição dos cabos ser de mais difícil acesso e ter um custo mais elevado. Este custo é de tal maneira elevado, que a substituição ou instalação de cabos subterrâneos é dez vezes superior à das linhas aéreas. Isto significa que qualquer decisão no âmbito de gestão de ativos deve ser bem fundamentada de modo a que sejam evitadas despesas desnecessárias. A análise de avarias/incidentes em cabos subterrâneos é importante de forma a determinar-se o seu impacto na qualidade de serviço da rede subterrânea, que atualmente é monitorizada e regulada segundo standards internacionais e nacionais.

O presente trabalho aborda a importância de se ter cada vez mais informação na caracterização de incidentes, visto que cada vez mais as *utilities* estão a apostar na otimização da gestão dos seus ativos. Isto é o resultado da mudança no paradigma do setor elétrico, que agora se foca na qualidade de serviço técnica e também na qualidade de serviço comercial. Neste âmbito, as utilities estão a começar a abordar o tema da necessidade de informação mais detalhada. Quanto maior for o detalhe da informação, mais precisas e especificas são as conclusões retiradas da sua análise. Isto resultará em decisões de gestão de ativos fundamentada, que espera-se que venha a ter um impacto positivo na qualidade de serviço

De forma a dar resposta ao problema proposto, o trabalho foi dividido em quatro fases, cujo objetivo foi determinar fatores que influenciam o comportamento dos cabos subterrâneos baseado nas características da rede subterrânea, mas também explorar o impacto da variação sazonal da temperatura e da carga. A primeira fase consistiu na aquisição da informação necessária ao estudo, que consistiu em dados de avarias e dados das características da rede subterrânea de MT. A segunda fase consistiu em caracterizar a rede subterrânea, através da compreensão da forma como esta está organizada e distribuída pelo território. De seguida, analisou-se a informação relativa a falhas dos cabos subterrâneos, determinando taxas de avaria, o impacto das avarias nos cabos na qualidade de serviço e identificar regiões com maior taxa de avaria. Esta fase incluiu a análise da sazonalidade das avarias nos cabos, dado existir perceção neste sentido. A quarta fase consistiu numa análise estatística de forma a determinar a significância dos comportamentos observados.

No desenvolvimento desta dissertação concluiu-se que um dos indicadores relevantes é a correcta caracterização dos activos avariados, em particular a idade dos mesmos. Neste âmbito, espera-se que no futuro seja possível efetuar um estudo mais detalhado incluindo esta informação. Outra conclusão importante deste trabalho foi o estudo da sazonalidade das avarias dos cabos, em que se observou um aumento do número de avarias, nos meses de primavera/verão, com o aumento da temperatura. Foi efetuada uma análise estatística de forma a averiguar se existia alguma correlação entre as duas variáveis, mas não foi obtida uma correlação muito forte. Uma possível explicação pode estar no facto de se terem utilizado previsões de temperatura para as datas das avarias dos cabos, em vez da temperatura real no dia/hora da avaria.

Os resultados desta dissertação realçam a importância da da aquisição de informação detalhada dos incidentes. Este trabalho avalia ainda possíveis causas para as falhas dos cabos, dada a perceção generalizada entre *utilities* que as causas dessas falhas se devem ao seu envelhecimento ou à sua deterioração acelerada devido a condições de operação.

Abstract

This thesis intends to fill a gap in the knowledge of MV underground cable failures in the Portuguese MV distribution network. Understanding cable failure is essential for making asset management decisions in the networks, as underground cable access for condition assessment or substitution is harder and more costly. The cost for cable replacement or installation is ten times higher than overhead cables, meaning that any decisions have to be well funded in order to prevent unnecessary costs. Additionally, cable failure analysis is important to determine their impact on the network's quality of service, which nowadays is tightly monitored and regulated by the sectors regulator and by international and national standards.

The present work addresses the topic of cable failure data, as utilities are increasingly investing in network information, particularly incident characterization . This is a result of changes in the energy sector's paradigm, which focuses on both technical and commercial quality of service. Utilities are starting to address data shortages by changing their acquisition processes and also the amount of detail collected. The greater the detailed information, the more precise and specific conclusions can be drawn, resulting in more precise asset management decisions which, ultimately will improve quality of service.

In order to address cable failures, the work was divided into four phases which intended to extract important behaviour based on the network's characteristics, but also exploring the impact of temperature and load variations on cable seasonal behaviour. The first phase was data acquisition regarding incidents and network information. The second phase consisted of characterizing the network, understanding how it was organized and spread throughout the country. Following this step, came the failure analysis, determining failure rates, the cable's impact on quality of service and identifying regions or characteristics with higher failure rates. This phase also included analysing cable failure seasonality, as it appears to have an affect. The fourth phase consisted of statistical analysis to determine the statistical significance of some observed cable behaviour.

During the development of this thesis it was concluded that failed cable age is an important parameter used for characterizing and studying underground network incidents. Another important conclusion was that is was possible to observe some seasonal cable failure behavior, which consisted of an increase in cable failures with temperature increase in spring/summer months. The statistical analysis performed determined that that the correlation existed, but was not strong. A possible explanation might be that the temperatures used were predicted temperature and not the cables actual temperature, and that further data could help explain this.

The results in this thesis highlight the importance of how incidents are registered and their importance for extracting information used in managing the Portuguese distribution network assets. Additionally, this work calls the attention for necessary information and possible causes for cable failure, as there is a generalized perception of cable failure due to ageing or accelerated deterioration caused by operating conditions.

Acknowledgements

I dedicated this section to all those who have helped me and contributed towards my success.

I would like to express my gratitude to my supervisor at FEUP, Prof. Hélder Leite, for his time and support throughout this process.

I would also like to thank my supervisor at EDP, Eng. Carina Morais, for her support and the opportunities provided. Also in EDP, I want to acknowledge the help of Sr Nelson and thank the Department of Technology and Information (DTI), particularly, Eng. Jorge Silva, for their time and inputs. I want to acknowledge the inputs from Eng. Jaime Guisado and Eng. José Ferreira Pinto and thank them for the time they took to listen, give advice and value my work.

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I dedicate this thesis to my grandparents, Mary and Paul, as they passed onto me the "Engineering gene". I hope I've made you proud.

To João, my boyfriend, my best friend, my companion, my everything. You have never left my side for 6 years. You are the MATLAB genius without whom this thesis could not be possible! You have also been there for me in all my important times, and every other ones as well. I want to thank you for the times when you wanted to sleep, but stayed awake just to keep me company. There really are not enough words (or pages in this thesis) to describe and thank everything. Thank you my Johnny!

I want to thank everyone else, that even in a small way, contributed for my success.

I thank you for choosing to read my thesis. Enjoy!

Emily Maggioli

“Wisdom is not a product of schooling
but of the lifelong attempt to acquire it”

Albert Einstein

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Abbreviations

ACER	Agency for Cooperating Energy Regulators
AM	Asset Management
ANN	Artificial Neural Networks
AO	Operational Area - *Àrea Operacional*
CDF	Cumulative Distribution Function
CI	Confidence Intervals or Confidence Bounds
CIGRE	International Council on Large Electric Systems
CPDV	Contaminants, defects, protrusions and voids
CRI	Consulting Registered Incidents - *Consulta de Registo de Incidentes*
D	Derivations
DGEG	National Directions for Energy and Geology - *Direcção Geral de Energia e Geologia*
DMA	Materials and Equipment Directives - *Directiva de Materiais e Aparelhos*
DRC	Client and Network Direction - *Direcção de Redes e Clientes*
EC	European Council
ED	Energy Delivered
EDF	Empirical Density Function
END	Energy Not Delivered - *Energia Não Distribuída*
ENTSO-E	European Network Transmission System Operators for Electricity
EU	European Union
ERSE	Energy Regulation Entity - *Entidade Reguladora dos Serviços Energéticos*
ET	Electrical Treeing
GICDN	Guide for Incident Classification in Distribution Networks
IEM	Internal Energy Market
IPMA	Portuguese Meteorological Institute - *Instituto Português do Mar e da Atmosfera*
IST	Lisbon Institute of Technology - *Instituto Superior Técnico*
J	Junctions
LD	Long Duration
MAIFI	Momentary Average Interruption Frequency Index
MLE	Maximum Likelihood Estimation
MV	Medium Voltage
NG	Natural Gas
PD	Partial Discharges
PdE	Delivery Points - *Pontos de Entrega*
PDF	Probability Distribution Function
PILC	Paper insulated Lead Covered
PTC	Client substation
PTD	Distribution substation

QoS	Quality of Service
RQS	Quality of Service Regulation - *Regulamento de Qualidade de Serviço*
RRC	Client Relations Regulation - *Regulamento de Relacções Comerciais*
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SEP	Public Service Energy Sector -*Sistema Eléctrico Público*
SEN	National Energy Sector - *Sistema Eléctrico Nacional*
SENV	Non-bound Energy Sector - *Sistema Eléctrico Não Vinculado*
SCADA	Supervisory Control and Data Acquisition
SD	Short Duration
SIT	System of Technical Information - *Sistema de Informação Técnico*
T	Terminations
TIEPI	Equivalent Interruption Time of Installed Power
WT	Water Treeing

Chapter 1

Introduction

1.1 Motivation

Underground cables are a fundamental element in any energy system, as they allow energy to be transported and distributed to consumer points. Therefore, if cables fail they will cause inconvenience for consumers, who will not have their energy supplied, and for the operators, who will have their quality of service indicators affected (increased). For this reason, it is important to access cable behaviour in order to make asset management decisions, either to replace or refurbish existing cables.

Cable failure is a rising concern among utilities, particularly underground cables, as they are harder access and are more costly to replace, as their installation is ten times higher than overhead lines.

There has been a growth in energy network stress and demands, because of an increase in consumer demands and also due to an increase in quality of service standards and demands. So failures have become a worrying issue, because they worsen the quality of service indicators. Without understanding what the behaviour is and what the main causes are, as well as determining what the most affected regions are, it is not possible to develop an efficient action plan. This thesis intends to be a contribution for a better understanding of MV underground cable failure and to contribute to the improvement of underground cable network's performance.

1.2 Goals and objectives

EDP Distribuição operators and collaborators have observed some behavioural patterns in cables, such as seasonality and also poorer cable performance in some regions . Additionally, energy system operators are subjected to tighter standards. The objective of this thesis is to gain a better understanding of what the behaviour is and parameters, which will aid in accessing cable failures and improving underground network performances.

This work intends to give a contribution in cable failure knowledge gap in the Portuguese distribution network and also improvements that will help increase this understanding in the future.

The objectives proposed for this thesis are:

1. **Characterizing the MV underground network**
   (a) Network organization;
   (b) Asset identification and classification;
   (c) Geographical dispersion of underground cables;
2. **MV underground cable failure**
   (a) Identification of behavioural patterns
   (b) Calculation and study of failure rates;
   (c) Impact of cable failure on the quality of service;
   (d) Seasonal study, determining correlation between failures and other variables like temperature or load;
   (e) Statistical analysis of cable failure data.

1.3 Thesis structure

This thesis is organized into five chapters (including the present one):

1. **Chapter 1**: Motivation, objectives/goals for the thesis, as well as its work organization/structure;
2. **Chapter 2:** Gives the QoS context to the thesis, explaining how this concept have changed, service standards and applicable regulation in Portugal;
3. **Chapter 3:** Summarizes utility experience with underground cables, including failure (data, numbers and seasonal behaviour) ageing and deterioration. It also addresses deterioration mechanisms and the impact of soil type and quality on cable heat dispersion. This chapter also addresses normal procedures for cable failure analysis, which include statistical analysis, correlations and development of prediction tools. It draws attention on information quality;
4. **Chapter 4:** Presents the results and conclusions of this work. This chapter addresses the following issues: Portuguese distribution network characteristics and organization, cable failure data analysis, cable failure statistical analysis and suggestions for improvements and future work.
5. **Chapter 5:** Summarizes the work's conclusions and suggestions for future developments.

Chapter 2

Quality of Service (QoS)

This chapter summarizes the changes in the electricity sector since the start of the liberalization process in Europe, as well as explaining how the electric distribution system is regulated in Continental Portugal (meaning that Madeira and Açores are not included).

The first part describes the regulation evolution in Europe and then, more specifically, in Portugal, creating a chronological description of major events and changes. The second part is a more specific explanation of how the electric sector is regulated in Portugal (Continent), focusing on the distribution network and quality of service. In this section there will be an emphasis on the quality of service regulation and how it relates to the work developed in this thesis, including the process of network incident registration and communication between electric utilities and the sector regulation entity - ERSE.

2.1 Electric sector evolution

2.1.1 European electric network regulation evolution

Over the past years the electric sector in Europe has suffered changes, the most noticeable being the liberalization and the creation of an **Internal Electricity Market** (**IEM**) [19]. Knowledge of these changes helps in the understanding of the evolution of the Portuguese network, which will be discussed in chapter 2.1.2.

Figure 2.1 summarizes the main events and changes in the electric sector in Europe, ordered chronologically.

As shown in the figure (Figure 2.1), the idea of an integrated European electric system dates back to 1951 [20] and 1985 [19]. But the liberalization initiatives only began in the 1990s, when the **European Union** (**EU**) and the Members States decided to open the electricity and **Natural Gas** (**NG**) markets to completion [21]. At this time, the countries' electricity markets were mostly monopolized and publically/owned by the state [1]. This coincided with the end of the wars (Second World War and Cold War) and the start of democratization processes in most European countries, which meant nationalizing activities that were previously privately owned or part of monopolies. **Liberalization** is the process of opening markets to competition [22]. This means that consumers can choose their service providers, offering customers a lower range of prices, thus making the economy more competitive [1, 22]. This meant a change in the market dynamic and structure, thus, the liberalization process requires the reform of the sector to accommodate the changes [1]. The diagram below (Figure 2.2) summarizes the key reform steps taken for the liberalization of the electric sector by countries in the EU according to [1].

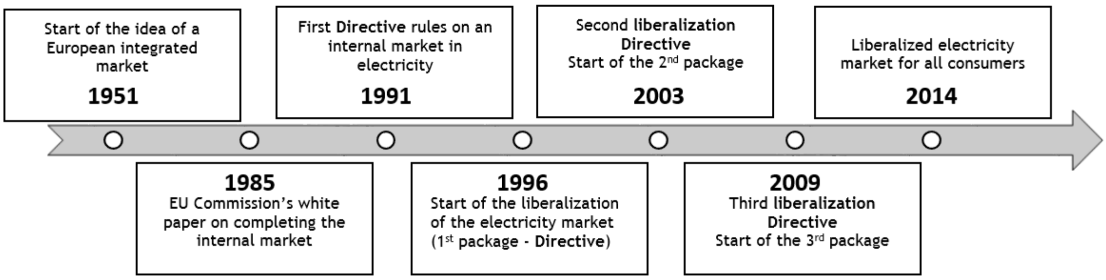


Figure 2.1: The chronology of European electricity market regulation

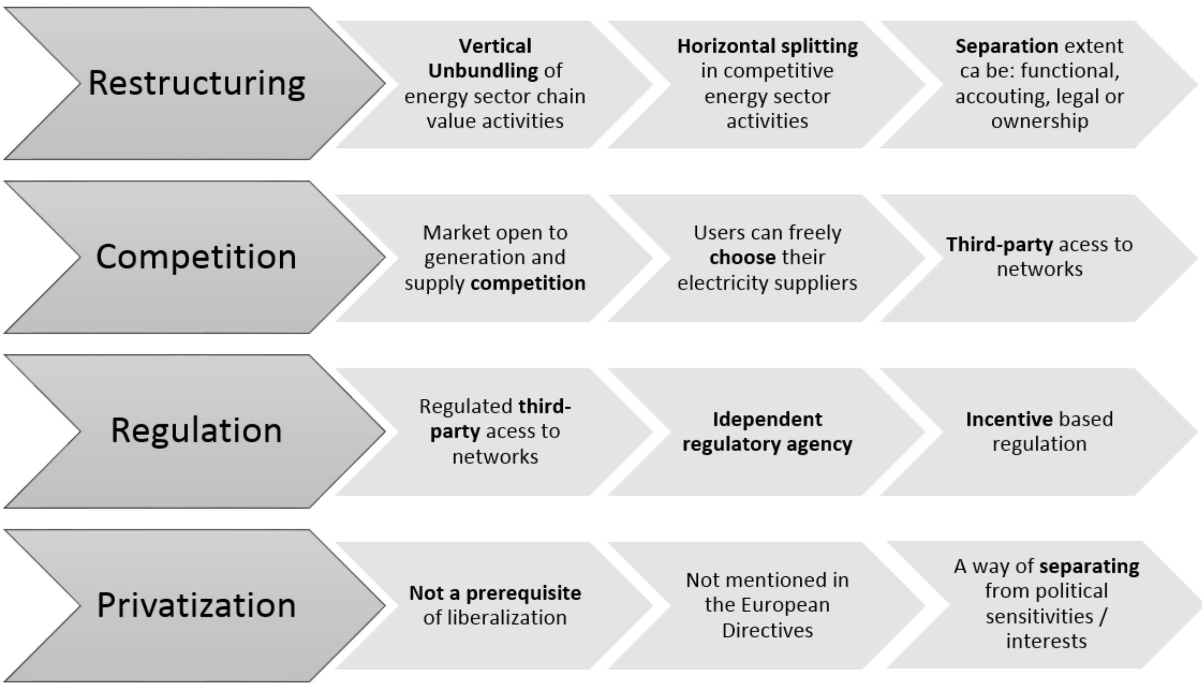


Figure 2.2: Key reform steps taken during the liberalization of European energy sector

The restructuring step consists of splitting the energy sector vertically and horizontally [1, 20, 23]. **Vertical separation**, otherwise known as **unbundling**, separates the energy chain value activities: generation, transmission, distribution and supply. Thus allowing the activities to become competitive – the **competition step** (see Figure 2.3). But only generation and supply are actually able to become competitive, as transmission and distribution are natural monopolies and cannot be competitive [1]. This means that they should be regulated to ensure competition in the liberalized market and allow **TPA** (**Third Party Access**) – the **regulation step** (see Figure 2.3). **Horizontal splitting**, on the other hand, only occurs in the competitive activities (generation and supply), allowing several participating organizations. This restructuring step is intimately related to the regulation and competitive steps. The figure below (Figure 2.3) shows the changes introduced by the reforms in the energy sector chain value. On the left (Figure 2.3 a) is the traditional (before liberalization) chain value and on the right (Figure 2.3 b) the liberalized market structure. As seen in b, there are several participants in the Generation (G) and Supply (S) activities.

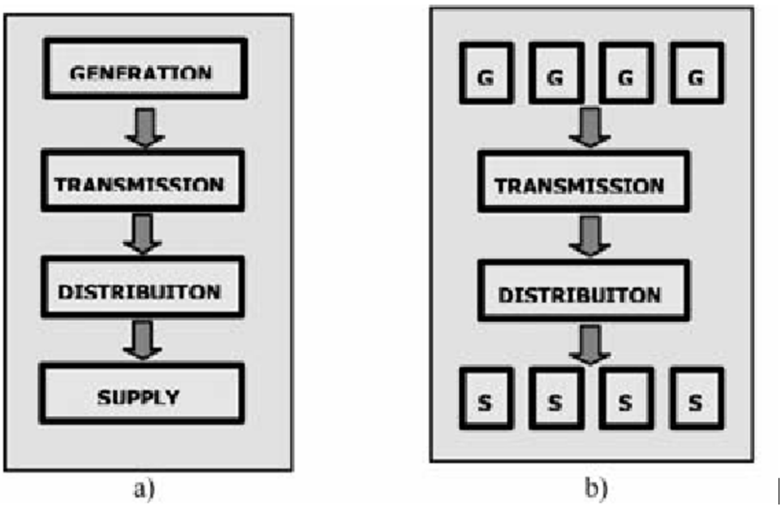


Figure 2.3: Electricity sector structure changes

It is not easy to separate these steps, because they all naturally lead to each other [19]. **Privatization**, which is not a prerequisite for liberalization, consists of separating the energy sector activities from the State. This separates the sector from the State's interests that might not always coincide with the liberalization principles [1, 22]. This also naturally means that there should be an independent entity to regulate the sector's activities [23]. This was the path chosen by most of the countries, but there are some exceptions regarding this last step, such as Norway and Sweden [1]. The European liberalization regulatory framework can be arranged into three legislative packages [21], as shown in the figure below (Figure 2.4), which represent the year bins in which the corresponding changes were introduced in order to better meet the needs of the IEM and liberalization objectives. The creation of the directives is carried out by the EU, but it is each country's responsibility to translate them into their laws and regulations within a defined period [21].

Figure 2.4: Stages of European energy sector liberalization

A liberalization package consists of several directives and regulations that aim at different sector activities, for example: electricity regulation, network cross-border electricity exchanges and IEM.

The first liberalization package was adopted in 1996 and had to be transposed into Member State's legal system by 1998 [21]. This package allowed only industrial clients to choose their service providers [21]. Only in 2003, with the second liberalization directive, were small and domestic consumers included in the liberalized market [21]. The translation of the directives into national laws had to be carried out in two parts: by 2004 all non-household consumers were eligible for the liberalized market and by 2007 all consumers were to be eligible [19, 21]. Besides allowing all customers into the liberalized market, the second directive also specified, for the first time, the establishment of sector-specific regulatory authorities in all Member States [19, 21]. But there was no requirement for this regulatory authority to be independent from politics or the state [21].

The figure below summarizes the main changes that occurred in the sector's activities with the described legislative packages (Figure 2.5) .

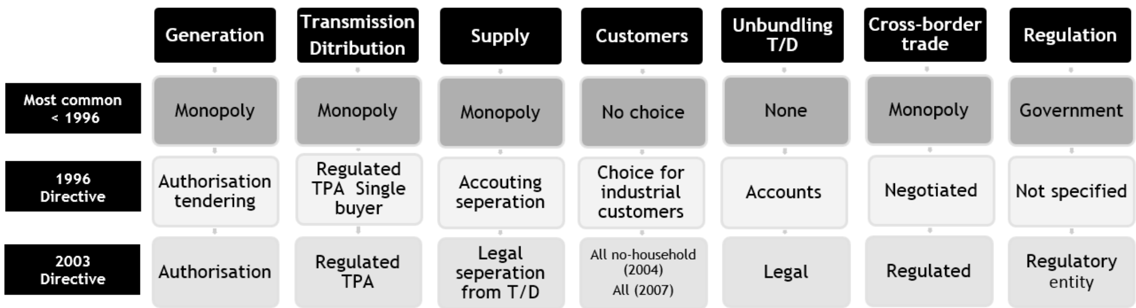


Figure 2.5: Stages of European energy sector liberalization: liberalization packages changes [1]

After all the changes introduced into the electricity market, the EU did not notice the desired changes, so a sector inquiry was launched in 2005 with the objective of identifying the barriers preventing greater competition in the electricity and gas markets [21]. This because the liberalization of the NG market started shortly after [21]. Based on the results of the enquiry (2007) a third liberalization package was emitted, with the aim of strengthening competition in the market, because the enquiry showed that the former packages did not lead to a uniform market model in Europe [19, 21]. The main shortcomings identified were: network congestion in several interconnections; the market still reflected the pre-liberalization structure (national and regional monopolies); customer's choice was still limited, and others [19, 24, 25]. This third package, among other things, better defined the role of the energy regulator as an independent entity independent of the Member State's government (stronger powers and independence of national regulators), not established in the 2003 Directive [19]. Other relevant improvements: tools to harmonize market and network operation rules at pan-European level; creation of **ACER** (**Agency for Cooperating Regulator Agencies**) and **ENTSO-E** (**European Network Transmission System Operators for Electricity**), both in 2011 [26]. The deadline for translation of the third liberalization package into national law was March 2011, but in 2011 the **European Council** (**EC**) decided for a complete market integration by 2014 [27].

The future challenges for the European energy market are discussed in chapter 2.1.3.

2.1.2 Electric network legislation chronology in Portugal

This section will discuss the chronological evolution and main changes of the energy sector regulation in Continental Portugal, which were carried out in parallel with the European directives or legislation packages. The focus in this thesis is exclusively on the continent. From this point on, whenever Portugal is mentioned, it refers to Continental Portugal, unless indicated otherwise.

After the Portuguese revolution in 1974 (25th of April) the energy companies at the time were nationalized and joined into one company which had the monopoly for all the sector's activities, as describe in the Decree-Laws nº 205-G/75 and nº 502/76 [23, 28].

The liberalization process in Portugal started with the publication of the Decree-laws 182 to 188 in 1995, which anticipated the approval of the European directive 96/92/CE [23, 29].This regulation defined the creation of the **Energy Service Regulation Entity** (**ERSE**) and a new **National Energy Sector** (**SEN**) now divided in **SEP** (**Public Service Energy Sector**) and **SENV** (**Non-bounded Energy Sector**) [23, 28]. The division of the SEN into SEP and SENV had the purpose of creating a regulated market (SEP) and independent liberalized market (SENV) [30], related to the non-competitive and competitive sector activities, respectively. At this time ERSE was merely responsible for regulating the continent, only becoming responsible for the NG sector and Portuguese autonomous regions (Madeira and Açores) with the publication of Decree-Laws nº97/2002 and nº 69/2002 [23]. At this point in time, the EU liberalization package had not discussed a regulation entity (see chapter 2.1.1).

ERSE was responsible, among other things, for emitting regulations and started doing so in 1998. The first version of the Quality of Service Regulation (RQS) was published in the year 2000 [23, 28]. This regulation was a result of the consumer's growing knowledge of their rights and rising quality standards [23]. ERSE's purpose and the RQS are further discussed in Chapter 2.3.

The publication of Decree-Laws nº 184/2003 and 185/2003 consolidated the second EU liberalization Directive 54/EC/2003 principles and also indicated the creation of **MIBEL** (**Iberian Market of Electricity**) [30]. This market between Portugal and Spain was not discriminated in the EU directive, it resulted from a memo signed by the two countries back in 2001 [28], but satisfied the part of the EU liberalization packages to strengthen interconnections. In 2006 the 1995 Decree-Law was revoked and a new one was published: Decree-Law nº29/2006. The aim of this regulation was to aid the operation of MIBEL. It also divided the SEN into four fundamental activities (new structure): production (ordinary and special regimes), transmission, distribution and supply. It transposed the Directive EU/2003/54 that stipulated:

- Ordinary regime production and commerce/supply are exerted in market regime;

- Network activities – transmission and distribution - are regulated and exerted under State concessions of the **RNT** (**National Transport Network**) and **RND** (**National Distribution Network**);

- **Low Voltage** (**LV**) networks are operated under concessions given by municipalities.

The figure below represents the new Portuguese electricity sector structure (Figure 2.6). Analysing the figure it is possible to distinguish the chain value on the right (Generation-Transmission-Distribution-Supply) that was affected by the changes suffered in the Portuguese electric sector and the two co-existing markets: regulated and liberalized. These two markets are a result of the opening to competition of only some of the energy sector's activities, for reasons already explained in chapter 2.1.1.

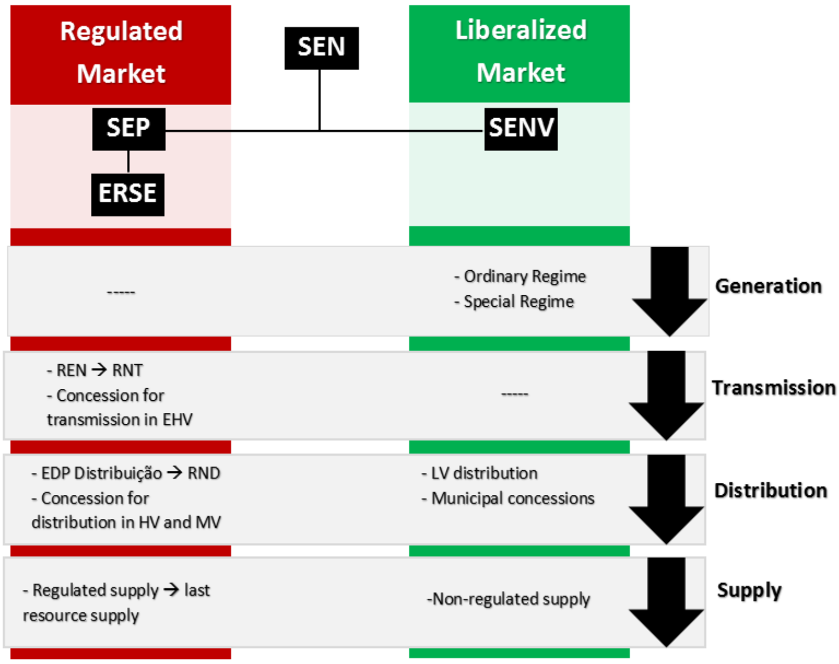


Figure 2.6: Electricity sector model in Portugal

By the 4th of September 2006 all consumers in continental Portugal could choose their energy supplier, anticipating the 2007 deadline imposed by the EU [29]. Since 2007 MIBEL has been fully operational with daily transactions between countries (Portugal and Spain) [31]. The changes that the energy sector undertakes nowadays (since 2006) are related to **QoS** (**Quality of Service**) improvements and enhancing transactions and regulation in MIBEL. One mentionable change was a new version of the RQS in 2013, with improvements regarding QoS parameters or indicators and event classification, especially in the case of extreme meteorological events [29] that affect the QoS. Figure 2.7 summarizes the chronological evolution of the main Portuguese regulations regarding the liberalization process.

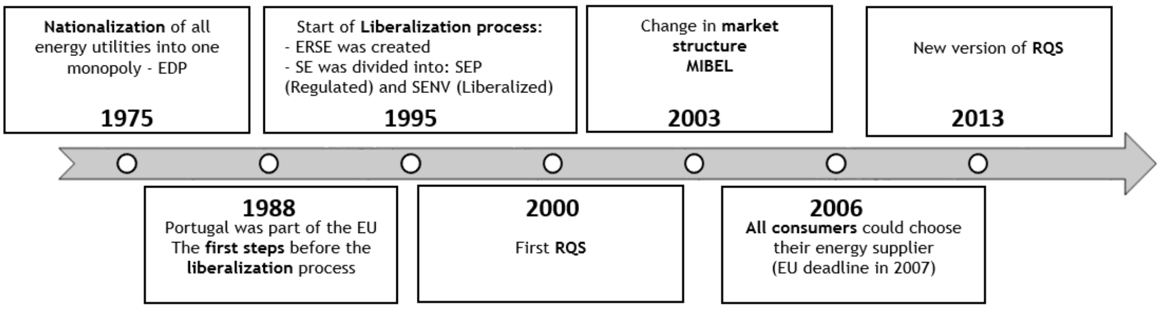


Figure 2.7: Portuguese energy sector regulation evolution

2.1.3 Future developments and goals for the network in Europe and Portugal

Since the start of the liberalization process and especially since the third liberalization packages, Europe entered an economic crisis. This recession meant that predicted electricity trends of a growth in energy consumption and trade did not take place. [32]. Slowly, countries and their economies are starting to recover as several countries are just finishing economic help programs, the EU decided to make a 10 year plan starting in 2010 until 2020, called "Europe 2020" [33]. This plan reflects the change in the growth and development models in Europe and has the slogan: *"For a smarter, inclusive and sustainable growth"* [34]. The energy strategy aims for *"competitive, sustainable and secure energy"* and its main goals are [35]:

- Reduce energy consumption;;
- Implement an internal market;
- Develop infrastructures;
- Improve technology;
- Protect customers;
- Reinforce the external dimension of energy policy.

The goals are still being refined, so changes are due to be introduced. But the areas for action remain: Energy efficiency, European infrastructure, Smart grids and International cooperation [35]. The 2020 Energy in Europe priorities are [35]:

1) Achieving an efficient Europe (20% savings by 2020)

Action 1.1: Buildings and transport;
Action 1.2: Reinforcing industrial competitiveness by making industry more efficient;
Action 1.3: Reinforcing efficiency in energy supply;
Action 1.4: Making the most of National Energy Efficiency Action Plans;

2) Building a pan-European IEM:

Action 2.1: Timely and accurate implementation of the internal market legislation;

Action 2.2: Establishing a blueprint of the European infrastructure for 2020-30;

Action 2.3: Streamlining permit procedures and market rules for infrastructure developments;

Action 2.4: Providing the right financing framework;

3) Empowering consumers and achieving the highest level of safety and security:

Action 3.1: Making energy policy more consumer-friendly;

Action 3.2: Continuous improvement in safety and security;

4) Extending Europe's leadership in energy technology and innovation:

Action 4.1: Implementing the SET Plan without delay;

Action 4.2: The Commission will be launching four new large-scale European projects;

textbf4.3: Ensuring long-term EU technological competitiveness;

5) Strengthening the external dimension of the EU energy market:

Action 5.1: Integrating energy markets and regulatory frameworks with neighbor countries;

Action 5.2: Establishing privileged partnerships with key partners;

Action 5.3: Promoting the global role of the EU for a future of low-carbon energy;

Action 5.4: Promoting legally binding nuclear-safety, security and non-proliferation standards worldwide;

The general EU goals for the energy market are: competitiveness, sustainability and security of supply [36]. Analyzing the future goals, it is possible to observe a focus on QoS, energy sources and customer awareness. Now that the market has been opened to competition in Europe, the next logical step is to invest in service quality and security and also environmental awareness. But, as mentioned, there are still several boundaries to overcome before really obtaining the IEM. This year (2014) presents a the deadline for the third European liberalization package and also discussions of future actions plans [34].

2.2 Energy quality of service: definition and importance

The electricity sector evolution reinforced the need for regulation. TThe regulators are responsible for national (ERSE – Chapter 2.3.1) and European (eg. ACER and CEER) regulation processes. This regulation includes power quality promotion, also refered to as QoS [23].

So what is QoS? The definition depends on the industry it is associated to, so there will be slight differences in definitions between industries. For the electricity industry, currently QoS is power quality and commercial quality [37] (Figure 2.8). This concept however has developed into what it is today, because before the liberalization period, QoS was basically ensuring the continuity of energy supply, in other words, ensuring that electricity was delivered to all consumer points [37]. Meanwhile, as the energy paradigm changed, so did the definition of QoS and its importance.

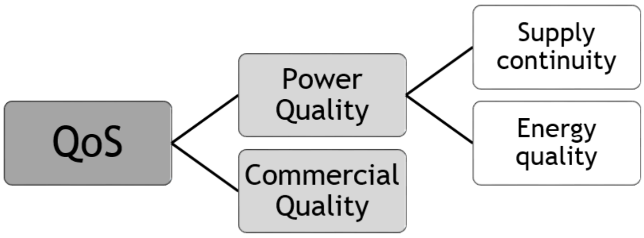


Figure 2.8: Quality of service organization

The QoS has become increasingly important because of the dependence of human activities on electricity, in such a manner that it is now considered an essential public good [23, 37]. Power quality can be divided into supply continuity and energy quality (Figure 2.8). Supply continuity is part of the QoS because any outages can have an impact on human activities, which nowadays include domestic consumers (not only businesses and industries) [37]. So each customer wants to have at their disposal the amount of electricity they need, when they want and it should be delivered with the necessary quality so that their appliances and equipment can run properly [23]. But power quality also includes energy quality, which means monitoring disturbances in electricity's characteristics, like voltage waveform, voltage dips, flicker, harmonics, etc. These kinds of disturbances affect the industry more critically because of the kind of equipment used and the consequences of poor energy quality. For example, voltage becomes distorted due to harmonic and asymmetric voltage drops across the network impedance, which leads to an increase of power losses in the AC power lines, transformers, rotating machines, decrease of the power factor, overvoltage or overcurrents by resonance phenomena, etc [23, 37]. Commercial QoS is considered, as energy supply is also a business, and operators must ensure customer satisfaction. Due to the growing importance of QoS, incentive/penalty schemes (Chapter 2.3.4) are used to promote network opertor's investment and QoS indicators have been created to monitor and quantify QoS. The indicators quantify a specific parameter of QoS and must obey international and national standards imposed by regulation and regulated by the sector's regulator. These indicators will be further discussed in Chapter 2.3.3.

2.3 Energy quality of service regulation in Portugal - RQS

2.3.1 Regulation entity: ERSE

This section will explain what ERSE is and what its role regulating the Portuguese electricity network. By understanding ERSE'S functions it will be easier to understand how ERSE, the RQS and the distribution utilities relate regarding incident registration, explained in Chapter 2.3.5.

ERSE was created in 1995 at the beginning of the liberalization process in Portugal. At the beginning it was only responsible for regulating the continental Portugal electricity market, later on adding the regulatory responsibilities for the NG market and the islands (Madeira and Açores). Currently ERSE is defined as a *"collective person detainer of public right, administrative and financial autonomy and of own patrimony"* and is governed by its own Status, as approved by the Decree-Law n^{o} 97/2002 and changed by Decree-Law n^{o}212/2012 while redacting the Decree-Law n^{o} 84/2013 [29].

The need for a regulatory agency or entity has to do with the change of the sector paradigm, as it is now open to competition, thus, there is a need for an organization with separate interests from the state's, in order to protect the customer rights and interests at the same time as maintaining market competition (in generation, supply and LV distribution). The regulator's independence is important for two reasons: first, to preserve stability and minimize regulatory risks; second, for credibility and temporal regulatory decision consistency [23].

ERSE is responsible for [29]:

- Protecting customer's rights and interests;
- Making information accessible and understandable to non-professionals;
- Making sure that the sector agents comply with their public service and other obligations, as stipulated by law and applicable regulations;
- Promoting market competition between sector agents; [1]
- Ensuring conditions for economic and financial balance in the energy's regulated sectors exerted in public service regime, when these are managed adequate and efficiently;
- Ensuring the energy sector operators fulfillment of their public service obligations and others defined by law and regulations, as well as concession contracts and licenses;
- Contributing to improving technical, qualitative, economic and environmental sector conditions by stimulating the adoption of good-practices for energy efficiency;
- Contributing for progressive improvement of technical, qualitative, economic and environmental sector conditions by stimulating the adoption of energy efficient practices;
- Preparing and publishing regulations;
- Fixing network access and transitional tariffs;
- Publishing regulated market prices;
- Making decisions about all matters subject to regulation ;

[1] Agents – Sector agents are companies or organizations responsible for any one of the electric sector's activities.

- Monitoring regulation application and fulfillment, and to apply sanctions when necessary;
- Issuing opinions.

The responsibilities listed above are general, applicable to energy and NG networks. Regarding the energy sector, the listed functions still apply can be detailed in a more sector specific manor [29]:

- Liberalization of the energy sector;
- Deepening and improving of MIBEL;
- Following sector's and sector's agents activities;
- Defining tariffs and prices for regulated activities;
- Promoting adequate levels of QoS;
- Elaborating regulations;
- Defining and monitoring connections to the network;
- Make sector numbers and facts available;
- Conducting inspections and audits.

Each year ERSE publishes a report concerning QoS in the energy sector, based on that sector utilities publish, as part of the RQS.

2.3.2 Quality of service regulation: RQS

This section will discuss the Quality of Service Regulation (RQS) evolution in Portugal. This regulation was the regulatory base for the work described in this thesis, which, among other things, it describes the incident registration procedure and classification, as well as how to calculate and reference values for the QoS indicators.

In a similar way as described in the previous section (2.2), QoS in the RQS is organized in [29]:

- Technical QoS (includes service continuity and energy quality);
- Comercial QoS.

The RQS establishes rules that define the minimum QoS that should be provided to clients, regarding [29]:

- Competences, responsibilities and obligations of entities involved;
- QoS indicators and QoS patterns/standards;

- Compensations to be paid when minimum standards are not fulfilled;
- Definition of clients with special needs and priority clients.

The figure below (Figure 2.9) summarizes the chronological evolution since the creation and main changes the RQS has undergone.

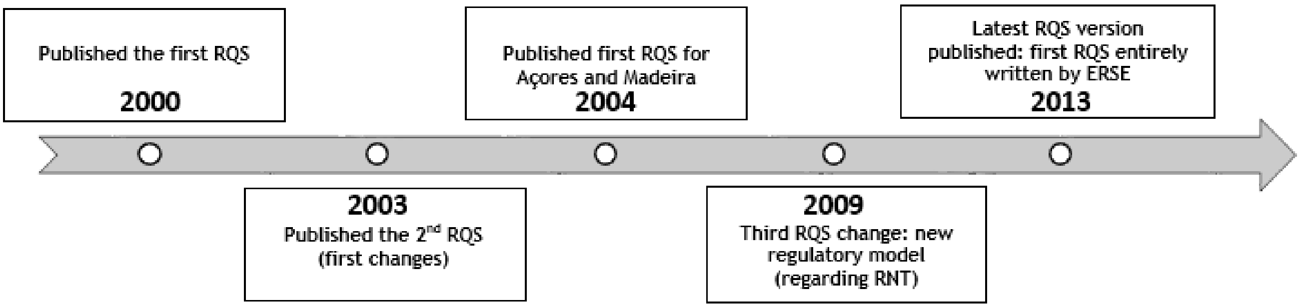


Figure 2.9: RQS chronological evolution

The main changes introduced with the new RQS in 2003, in relation to 2000, were [38]:

- Quality service regions;
- QoS indicator calculation methodology;
- QoS patterns;
- Methodology for calculating and paying compensations regarding QoS pattern failure.

Some of these definitions will be further discussed in Chapter 2.3.5.

Until 2004 there was only one RQS and it only concerned continental Portugal. During this year (2004) two new RQSs were published for Madeira and Açores regions, which were applied in 2006 and 2007 to the regions, respectively [39]. The three RQS (for the continent, Madeira and Açores regions) established the standards for QoS regulation and were written by **DGEG** (**Direcção Geral de Energia e Geologia**), for the continent, and regional directions for industry, commerce and energy in the Madeira and Açores regions [40]. ERSE was responsible for aproving these regulations.

In 2013 a new and the most recent version of the RQS was published. For the first time there was a single RQS for regulating the continent and autonomous regions (Madeira and Açores), which was written and approved by ERSE. This new version included, among others, changes in the network operator's obligations [2, 29].

With every change in the RQS, ERSE has successively implemented new goals to improve QoS in Portugal. Currentyd iscussionss are undergoing for a new RQS version, but there is no indication, so far, of a publication date [29].

2.3.3 Quality of service indicators

All information described here was based on [2]. There are other indicators regarding QoS, like commercial QoS indicators, but this chapter only discusses supply continuity indicators, as they are the only ones related to the work developed in this thesis. For more indicators check [2].

According to RQS there are five defined QoS indicators for **MV networks**, two of which have minimum standard values defined. These indicators are: **TIEPI** (**Equivalent Interruption Time of Installed Power**), **SAIFI** (**System Average Interruption Frequency Index**), **SAIDI** (**System Average Interruption Duration Index**), **END** (**Non-distributed Energy**) and **MAIFI** (**Momentary Average Interruption Frequency Index**), of which only SAIFI, SAIDI have regulated minimum defined patterns. The tables below list the indicator's global pattern values per QoS Region and individual pattern values, respectively in tables 2.1 and 2.2.

Table 2.1: General standard MV indicator values per QoS Region in Continental Portugal [2]

Indicator	QoS Region	Pattern Value
SAIDI (hours)	A	3
	B	4
	C	7
SAIFI (interruptions)	A	3
	B	5
	C	7

Table 2.2: Standard MV indicator values per QoS Region in Continental Portugal [2]

Indicator	QoS Region	Pattern Value
N^{o} of Interruptions	A	8
	B	12
	C	16
Total Interruption Duration (hours)	A	4
	B	8
	C	12

As mentioned before, the RQS defines three QoS service regions. The classification of these regions is made according to the following criteria (Table 2.3):

Table 2.3: Quality of service Region classification [2]

QoS Region	N^{o} of clients	Description
A	> 25000	District capitals of continental Portugal
B	2500 < clients < 25000	—
C	—	Remaining regions

Before explaining in more detail how each indicator is calculated and what it means, two definitions need to be clarified (definitions according to RQS):

- **SD** (**Short Duration**) interruptions: interruption with a duration equal or superior than 1 second and inferior or equal than 3 minutes (0<t<180 sec);

- **LD** (**Long Duration**) interruptions: interruption with a duration longer than 3min (t>180 sec);

The indicator TIEPI represents the equivalent interruption time of installed power, for long interruptions, analyzed during a certain period (trimester or civil year). The units are minutes and it is calculated by the following expression:

$$TIEPI_{MT} = \frac{\sum_{j=1}^{k}\sum_{j=1}^{x} DI_{ij}PI_j}{\sum_{j=1}^{k} PI_j} \tag{2.1}$$

where:

DI_{ij} - durations if the LD interruption i at PdE j;

PI_j - installed power at PdE j (**PTC** ou **PTD**);

k - n^o of PdE in the distribution network (PTC e PTD);

x - n^o of LD interruptions at PdE j.

The indicator END represents an estimated value of energy that is not distributed to the respective PdE, caused by LD incidents. The expression below explains the calculating procedure and the units of this indicator are MWh.

$$END = \frac{TIEPI_{MT}ED}{T} \tag{2.2}$$

where:

$TIEPI_{MT}$ - TIEPI of the MV network;

ED - energy distribued to the MV network by the network distribution operator, calculated from the delivered energy by the transmission operator and the producers connected to the distribution network, deduced by the loads of the HV consumers connected to the HV network;

T - Period considered

The indicators MAIFI and SAIFI are similarly calculated, except MAIFI only accounts for SD incidents and SAIFI for LD incidents. SAIFI represents the average number of LD interruptions that affected the PdE in the distribution network, over a certain period (trimester or civil year). MAIFI represents the same as SAIF but regarding SD incidents. None of these indicators have any defined units. The expressions below allows for the calculation of the two aforementioned indicators:

$$MAIFI_{MT} = \frac{\sum_{j=1}^{k} BI_j}{k} \tag{2.3}$$

where:

BI_j - n^o SD interruptions at the PdE (PTD e PTC), during the considered period;

k - n^{o} of PdE of the MV distribution network (PTC e PTD).

$$SAIFI_{MT} = \frac{\sum_{j=1}^{k} FI_j}{k} \tag{2.4}$$

where:

FI_j - N^{o} of LD interruptions at the PdE (PTD e PTC), during the considered period;

k - N^{o} of PdE in the MV distribuition network (PTC e PTD).

Finally, SAIDI represents the average duration of LD incidents occurred at PdEs of the MV distribution network, during the analyzed period (trimester or civil year). This indicator's units are minutes and it is calculated according to the expression below.

$$SAIDI_{MT} = \frac{\sum_{j=1}^{k} \sum_{j=1}^{x} DI_{ijMT}}{K} \tag{2.5}$$

where:

DI_{ijMT} - duration of the LD interruption i at the PdE j;

k - N^{o} of PdE in the MV distribuition network (PTC e PTD).

x - N^{o} LD interruptions a the PdE j.

2.3.4 Incentives to improve the quality of service

Incentives have been included in the RQSs, and are important because they lead to to QoS and also network improvement. The focus of this chapter is to explain how incentives work in the Portuguese energy sector, according to the RQS. Regarding QoS, the RQS only defines incentive mechanisms to improve the service continuity in HV and MV distribution networks, in continental Portugal [2]. The Figure 2.10 represents the model for calculating the incentive and it is based the **END** (**Energy Not Delivered**) indicator. This is indicator was chosen over others because it quantifies the non-continuity of service by quantifying the inconvenience caused by the absence of energy supply. Logically the impact is higher when the consumption is also higher [23]. In other words, it evaluates the impact of the energy service interruptions in relation to use/consumption. The indicator can be calculated according to the expression 2.2, presented in the previous Section (2.3.3.

The regulator defines the objectives and the incentives, but ultimately it is up to the company the way they take in order to fulfill those objectives [23]. In other words, in this model, client compensation works as a sanction for not satisfying the stipulated level of quality. The Figure below represents the incentive model (Figure 2.10) and it is defined by five parameters [23]:

- END_{REF} - Reference END, in kWh;
- $\Delta-$ END$_{REF}$ variations;

- VEND - END Valorization, in €/kWh;
- RQS_{max} - Maximum prize defined, in €;
- RQS_{min} - Maximum penalty, in €;

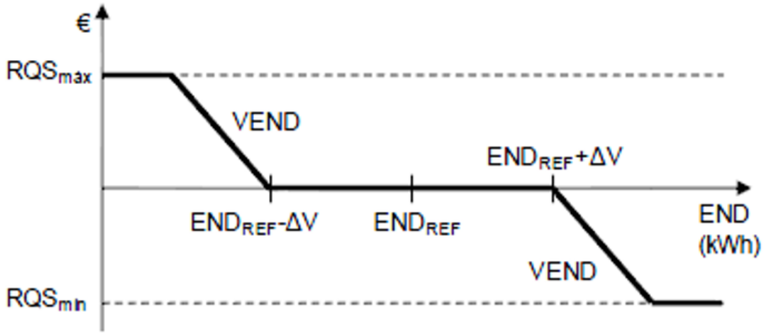


Figure 2.10: Service continuity incentive calculation model [2]

The model incentives or penalties are calculated according to 3 situations [2]:

1. When $END_{t-2} < END_{ref,t-2} - \Delta V$:

$$RQS_{MT,t-2} = min\left\{RQS_{max,t-2}, [(END_{ref,t-2} - \Delta V) - END_{t-2}]VEND_{t-2}\right\} \tag{2.6}$$

2. When $END_{ref,t-2} - \Delta V \leq END_{t-2} \leq END_{ref,t-2} + \Delta V$:

$$RQS_{MT,t-2} = 0 \tag{2.7}$$

3. When $END_{t-2} > END_{ref,t-2} + \Delta V$:

$$RQS_{MT,t-2} = max\left\{RQS_{min,t-2}, [(END_{ref,t-2} + \Delta V) - END_{t-2}]VEND_{t-2}\right\} \tag{2.8}$$

Situations 1 and 3 refer to incentive and penalty scenarios, respectively, while situation 2 does not lead to any kind of payment either way.

2.3.5 Incident registration and classification

This section explains the process of incident registration and classification based on the RQS. This is important for comprehending the registered incident databases that were used for the development of this thesis and will be further explained and discussed in Chapter 4.

The figure below (Figure 2.11) summarizes the procedure for incident registration and how it relates to QoS index calculation. Some incidents like extreme weather need to be approved by the sector regulator – ERSE – and are not accounted for when calculating the indexes.

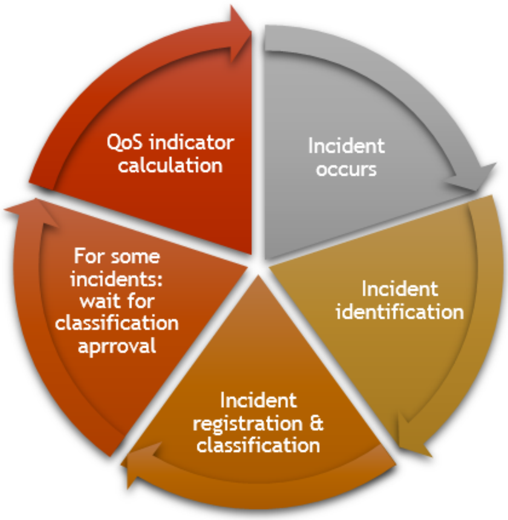


Figure 2.11: Incident cycle

The RQS [2] describes the process of incident registration and classification. For a start, the information that must exist mandatorily is:

- The facility where the incident originated;
- Date of interruption's start and finish;
- Incident cause;
- Proof of communication action or any prior disclosure;
- Localization proof, especially important in situations caused by clients.

In order to complete the incident register, identifying the affected network element and phases as well as the control, command and protection center's actions must be registered or documented. All incidents should have an identification code, to tell them apart. And all incident related information should be kept for a minimum period of 5 years [2].

According to [2] interruptions are classified according to their origin, type cause. Based on this, interruptions can be classified as shown in the table below (Table 2.4).

Predicted incidents consist of interruptions with client agreement, service reasons or public interest, for which clients are informed in advanced according to the **RRC** (**Commercial Relationships Regulation**). All other interruptions are considered accidental incidents/interruptions.

The causes of incidents: [2]:

Public interest reasons:

- Interruptions resulting from national emergency plans, declared under specific/applicable legislation, namely resulting from civil emergency plan and energy crisis;

- Interruptions determined by a competent administrative entity;

Table 2.4: Incident classification [2]

Origin	Type	Cause
Generation, transmission or distribution	*Predicted*	Public interest reasons
		Service reasons
		Reasons attributable to the customer
		Client agreement
		Other networks or facilities
	Accidental (1)	Security reasons
		Fortuitous reasons
		Compelling reasons
		Exceptional events
	Accidental (2)	Network
		Other networks or facilities

- Currency possibility must have had proper disclosure from network operators with a least 36h notice, fulfilling the obligations in the RRC;

Service reasons:

- Interruptions caused by the need for maneuvers, connections works, repairs or network conservation;
- Possibility of occurrence must have had proper disclosure from network operators with a least 36h notice, fulfilling the obligations in the RRC;

Reasons attributable or agreed with the consumer: interruptions caused through agreements with client or in situations referred in the RRC;

Security reasons: interruptions that occurred in situations where maintaining service continuity will question the security of people and goods, according to RRC;

Fortuitous reasons: Interruptions that occurred under conditions described in Article n^{o} 7 of the RQS;

Compelling reasons: Interruptions that occurred under conditions described in Article n^{o} 7 of the RQS;

Other networks or facilities Interruptions that originated in others' networks or facilities belonging to other operators, producers or clients;

Exceptional events: Interruptions that occurred under conditions described in Article nº 8 of the RQS;

Network: Interruptions that occurred under conditions that cannot be classified as any of the previous categories, so they are consider the respective network operator's fault and can be classified as caused by:
- **Atmospheric phenomena:** lightning discharges, rain, floods, snow, ice, hail, fog, wind or pollution;
-**Natural causes:** animals, tree falls, landslide or interference of foreign objects to the network or production centers;
-**Internal origin:** project or assembly mistakes, failure or inadequate use of equipment or materials, maintenance activities;
-**Other causes:** all causes not included in the above or are unknown.

In the case of incident categories referred to in article nº8, the network operator needs to make a request to ERSE, and if approved will be excluded from index calculation. For more details on request procedure and regulator evaluation, see the RQS regulation [2].

2.4 Importance of this chapter for the work developed in this thesis

This chapter's goal is to contextualize in terms of regulation, importance and history/evolution of the work developed in this thesis, as cables have an impact on the QoS.

The QoS has become a growing concern for utilities across Europe and the rest of the world, although the focus of this work and its contextualization regard Europe, more specifically Portugal, as this thesis was developed in cooperation with the Portuguese energy distribution operator. This concern for quality in the energy sector has developed from just satisfying continuous supply of energy to include energy quality (e.g. voltage waveform and harmonics) and costumer service. This reflects a change in the energy paradigm (liberalized), which also resulted in an increase in standards for QoS indicators (which quantify technical QoS) and costumer service. The sector's regulators monitor and reinforce measures to ensure the compliance with regulation and standards.

Cable failures will have an impact on the QoS, as they can result in service interruption, which can be quantified by determining their impact through the calculation of the QoS indicators. Understanding their behaviour and impact will help to make maintenance decisions to prevent failures or reduce their impact. The next chapter summarizes studies for causes and utility experience with cable failure.

Chapter 3

Underground cables studies and experience

This chapter is divided in four parts. The firsts is an explanation of cable evolution, from the first oil filled cables to the extruded/dry cables, that are widely used nowadays and are replacing older cables because of their added performance. The second part lists and explains factors taken into consideration when designing cables, as newer technologies are developed to improve cable behaviour. Also the main cable deterioration and ageing factors are listed, which help to understand cable failure situations. The third part summarizes some utilities' experience with cable failure and also the importance of proper data acquisition in order to conduct studies on important cable failure features, like failed cable age, which is a missing information in lots of the utilities databases.The fourth presents statistical studies and prediction model procedures in a generalised way, as they summarize several observed models published in papers. In the end a good idea of general observed cable behaviour and study models, from which important conclusions are drawn an taken in account in asset management.

3.1 Underground cable evolution

3.1.1 Underground cable evolution highlights

The underground MV distribution network does not consist of a single kind of cable - not homogeneous. The variety and quantity (length) of cable types is related to the network history, but also to component improvements over the years. Whenever a better kind of cable is introduced into the market, it just is not possible to substitute all the network's cables with the new variety. This mainly because of the high cost of underground cable installation/substitution (ten times higher that overhead lines), but also due to other restrictions, like city hall authorization, etc.

This section will present a brief description of the cable evolution, mentioning the most widespread used cable types. The awareness of the existence and reason for different cable types will help to understand the work and results of Chapter 4.

The figure below represents the common constitution of a MV underground power cable nowadays (Figure 3.1).

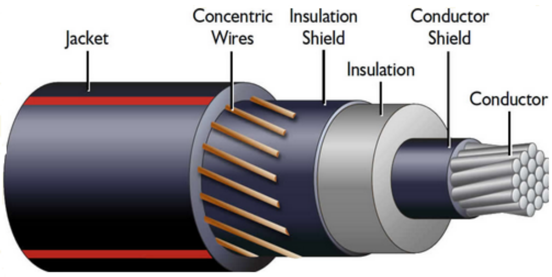


Figure 3.1: General underground cable constitution [3]

Cable have changed over the years, but the most relevant changes were in cable insulation, as its failure or defects are responsible for a large percentage of cable failures.

The most common materials used for insulation over the past 124 years (since 1890 to date) are summarize in the diagram below (Figure 3.2), which was based on [41]. These different types of cables reflect the evolution of materials and techniques used in the industry. As the figure shows, the insulation materials can be divided into paper/oil impregnated and synthetic, the second being the most widely used currently [41].

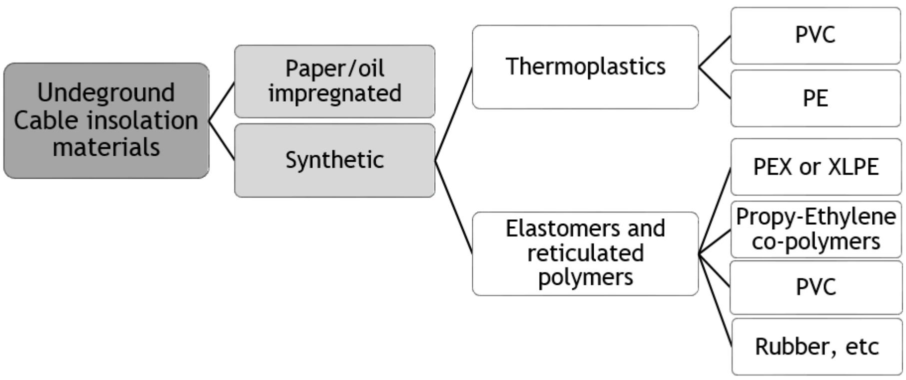


Figure 3.2: Underground cable isulation materials

The first underground power cables installed were paper-oil insulated. These first cables were not very flexible and were directly buried in the ground. The 40 year life expectancy is thought to have started with these cables, as they were successfully used for 43 years in the US [42]. Insulation developments lead to the **PILC** insulated cables (**Paper insulated lead covered cables**) [42]. PILC cables were the predominant power cables around the world throughout the twentieth century [42]. Emanuelli of the Pirelli Company in 1972, is known for perfecting this technology [43].

In 1993 the **Cross-linked polyethylene** (**XLPE**) insulation was developed by General Electric Company [43]. As mentioned before, until this time the predominant cables were fluid-impregnated. But with the introduction of this synthetic material, underground power cable performance exceeded the previous technology. Nowadays XLPE cables are the predominant insulation and with proven higher performance, even though their manufacturing process has undergone several improvements (Eg:: TR-XLPE, otherwise known as the tree retardant XLPE insulation) [42, 43].

Besides insulation developments, other cable improvements worthy of mention, such as the introduction of the shield and armor – for cable mechanical protection – and jackets for making the cable more water resistant [42, 43].

Chapter 3.2 will discuss some downfalls of the mentioned cable types, focusing on ageing and deteoration phenomena.

3.1.2 Distribution network underground cables in Portugal

In continental Portugal the cable topology is the one shown in Figure 3.2, which is specified in DMAs. **DMA**s are **Materials and Equipment Directives** (from the portuguese **Directiva de Materiais e Aparelhos**), are part of the regulation for electrical related procedures in the distribution network in Continental Portugal. EDP Distribuição, an EDP sub company, is responsible for publishing these rules, which are based on European and International standards. The normative regulations published by EDP Distribuição are organized in five groups of norms, including DMAs, which define procedures, equipment specification and others [44]. The diagram below summarizes these norm groups (Figure 3.3).

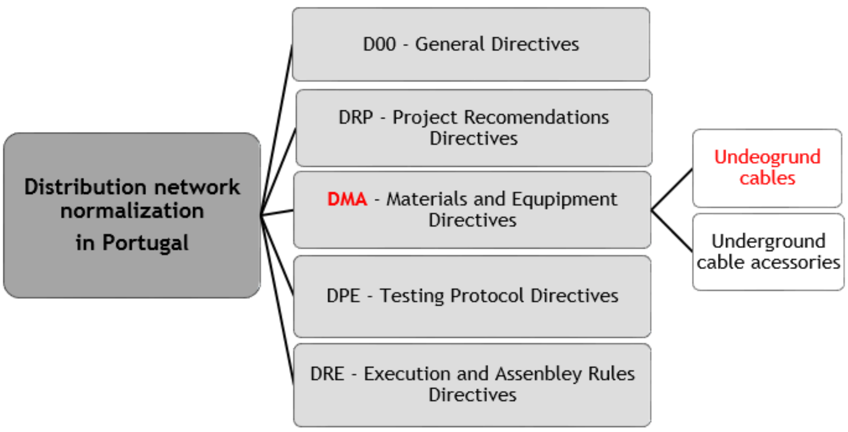


Figure 3.3: Portuguese distribution network normalization organization

The **DMA-C33-251/N** [4] defines the minimum accepted cable characteristics for each voltage level, as well as cable installation and testing procedures. The tests are conducted on installed cables to prove that they conform to the specified DMA characteristics. The figure below (Figure 3.4) represents the accepted cable constitution since July 2008 (release date of the mentioned DMA).

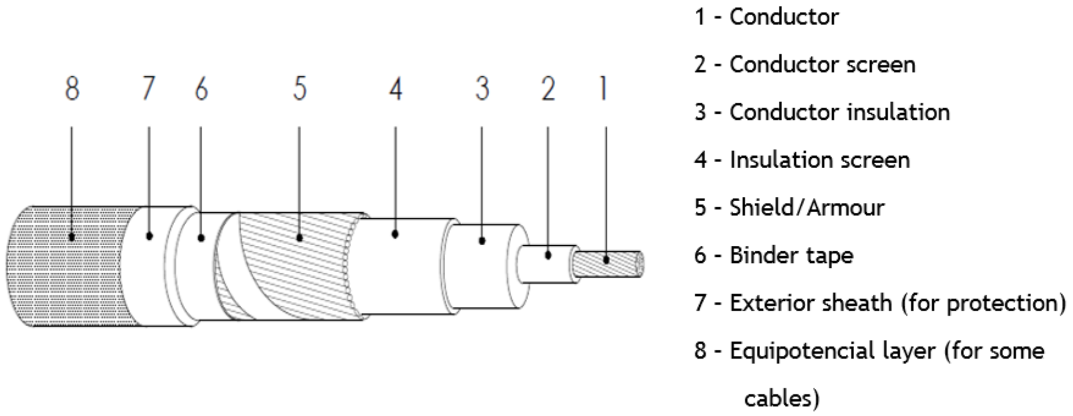


Figure 3.4: Underground cable isulation materials [4]

Regarding cable acessories, **DMA-C33-833/N** specifies the accessories for MV extruded cables with a solid dielectric [45]. In a similar way to the cable DMA, this describes all procedures for and characteristic of cable accessories (Eg:: terminations, joints, etc) [45].

According to [5] (an internal document study), the underground cables in EDP's distribution network can be organized into cable generations, that basically divides the cables used in certain years in the MV underground network in Portugal.The cable types used over the years are summarized in the diagram below (Figure 3.5) [5]. Nowadays dry cables constitute a larger percentage of the MV underground network [5].

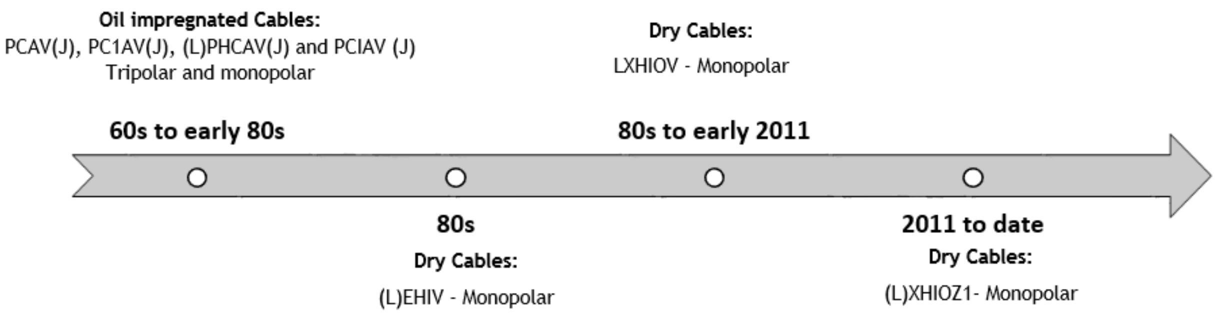


Figure 3.5: Underground cable insulation materials [5]

The Table 3.1 below summarize the designation of cables over the years [1], including the current cable designation. This table information was based on the cable DMA [4].

The cables with **non-fire propagation** (**frt**) are only used in substation feeder underground cables [4, 5]. Currently, the new cables installed have an additional property: they are organized and assembled in sections. This makes the cables substitution process easier and cheaper, so instead of substituting a considerable cable length (when in some cases only a small section is affected), EDP can narrow this to a problematic section. It is also possible to have a certain cable length with some parts patched using this new technology. This also possible due to the

[1] Cable designations must obey norms, the most recent one for cable designation is NP665

improvements in cable accessories, that are not thermoretractable (accessories are heat retractable) but installed with a cold retractable technology, which reduces the risk of a bad installation as the process is simpler[45].

Table 3.1: Underground cable designations over the years

Cable part	Symbol/letter	Meaning
Conductor	(no letter)	Rigid copper conductor
	L	Stranded aluminium conductor
Insulation or Sheath	P	Paper
	C	Lead
	V	PVC (Polyethylene)
	J	Juta
	E	PE (Polyelhylene)
	X	PEX or XLP (Cross-linked Reticulated Polyethylene)
	Z1	Polyolefin or Shrink film
Shielding	H	Collective shielding
	HI	Individual shielding
Armour	A	Steal tapes
	O	Copper lines
Other features	(be)	Tight/water proof
	(ftr)	Non-fire protection

Underground cables are generally directly buried in the ground at least 1m in depth, being covered in a thin layer of sand, followed by clean soil. At 0,1m over the cables several planks with a considerable mechanical resistance are placed (specified in [5]). Only in crossing areas (like crossing streets, highways, etc.) are the cables covered in concrete, always at least 1m in depth [5].

3.2 Factors that affect underground distribution cable performance

3.2.1 General cable design considerations

The underground cable improvements are a result of the utilities' concern with cable life expectancy that, in some cases, can be 40 years [46]. Ageing and deterioration processes are a result of environmental and operating conditions. The author [46] makes an analogy between cables and car use. The operation variations that cables are subjected to are what causes a more rapid deterioration, like in a car, if it is driven in variable terrain at variable speeds. Manufacturers use techniques and designs to prevent against known deterioration mechanisms [46]. There is more detail on ageing and deterioration processes in Section 3.2.2. The stages that a new cable (or improvement) follows are described in Figure 3.6. Improving one of the following described aspects can lead to an improved or new cable (Eg: cable design, material selection and manufacturing process). In the end, the manufacturer determines life expectancy through ageing tests that should result in either longer time to fail or higher dielectric strength. Or as an alternative, determine life-expectancy through statistical tests [46]. Either way, it is not possible to determine the exact life expectancy, mainly because the current technology cannot produce zero defect products [46]. When developing a new or improving a cable, data from previous similar cable models or materials should be analyzed to determine weak points (improvements).

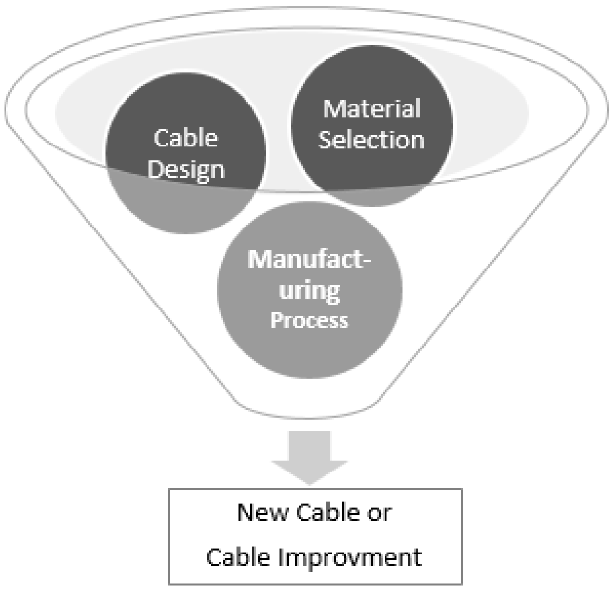


Figure 3.6: Cable design considerations

The main problem during manufacturing is contamination. Ideally, contaminant free material should be used, but producing and shipping this is not possible. But any improvements in this area affect cable quality, at little or no cost for the final user [46]. As seen in Chapter 3.1, nowadays cables are manufactured using extrusion, a process that reduces contamination.

Cable design takes into account manufacturer and user input. The main identified constraints include compatibility with existing accessories or the manufacturing capabilities of the cable producer. Cable design consists of decisions regarding the following factors: conductor section, conductor type, insulation thickness, insulation shield and jacket [46].

The costs of the conductor section increases with size, because it affects the size of the remaining cable parts. But, on the other hand, a larger section can run cooler than a small section, for the same load. High temperature is a factor that accelerates ageing, so the section should be chosen to run cool in normal operating conditions. Conductor types can be stranded or solid, solid being the cheapest. However, for long cables the conductor must be stranded. This kind of conductor type is more susceptible to water deterioration, so the space between strands can be filled with an insulating compound, but at an increase in cost. On the other hand, stranded conductors are more flexible, thus less sensitive to some mechanical forces. Similarly, the thickness of the insulation also increases the cost, but it also increases the cable cable lifetime. With thicker insulation, the cable has a higher voltage stress resistance. The insulation shield varies with the cable diameter and is costly. But if the cable has an outer protective jacket, the insulation shield can be thinner, thus reducing cost, without reducing cable performance. The cable jacket, which covers and encapsulates the neutral wires, is strongly recommended [46]. This also works as a water ingress retardant and protects cable from abuse, making it a good insurance against neutral wire corrosion.

Material selection for the shields, insulation and jacketing layers should take into account the interaction among cable components. The most widespread choices are naturally filled or tree retardant insulation and either polyethylene, semiconducting ethylene polymers or PVC for jackets [46].

3.2.2 Distribution cable ageing and insulation deterioration

This section will describe the main ageing and failure mechanisms, as well as the advantages and limitations of available diagnostic tests, for the different insulation systems used in distribution cable networks. The information obtained from these tests/diagnostics, will help electric utilities can decide what the best strategy is for their underground network (to maintain, repair, refurbish or replace).

Distribution cable systems represent a large capital investment for electrical utilities and have to be highly reliable in order to avoid revenue losses, particularly from premature cable failures [17]. As the figure below (Figure 3.7) shows, the expected higher failure rates in a cable's life cycle occur in premature failures or ageing failures [47]. This curve is also known as the **"bathtub" curve**, because of its shape. The explanation for the early or premature failures has mostly to do with bad installation or cable defects from manufacturing or transport [48]. **Ageing** is the result from cable operation and exposure to ageing mechanisms, as it loses its original characteristics. Generally premature failures are not considered, because the assumption is made that this part of the cable lifetime is lived in the manufacture's lab or detected during installation and testing procedures [47].

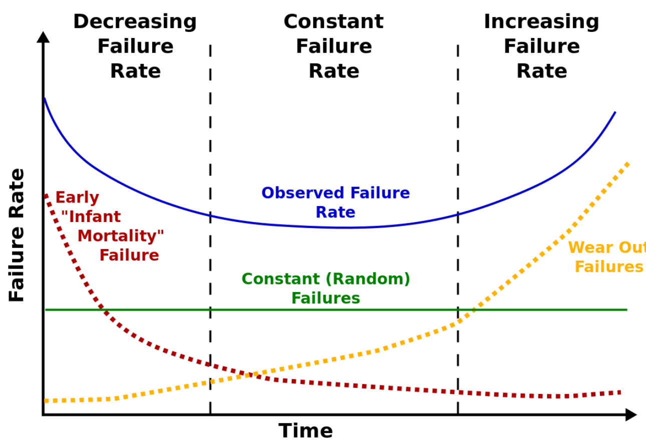


Figure 3.7: Cable lifetime curve – bathtub curve [6]

Currently utilities have ageing networks and are being faced with decisions to maintain, repair, refurbish or replace their cable systems. These decisions are based on cable conditions, especially electrical insulation condition. Further electrical utilities' experience with underground cables will be discussed in Chapter 3.3.

Insulation ageing or deterioration is a key factor in power cable failure [49]. In such a matter, that **CIGRÉ** (**International Council on Large Electric Systems**) has addressed the ageing factors and diagnostics of cable systems by publishing three reports covering fluid-filled and extruded cables [17, 50, 51, 52]. These types of cable insulation will be the focus of this chapter. In the case of fluid-filled only paper/oil insulated will be considered, excluding the gas insulated cables.

Diagnostic tests can provide information about unobservable cable conditions, like insulation condition. However the usefulness of these tests is limited [49]. The first reason is that the tests are generally not completely definitive in identifying cable condition, and the second reason is the cost of these tests are high and may even cause, in some cases, equipment failure [49]

The ageing mechanisms are similar for each of the insulation types, differing the stresses at which ageing starts [17]. According to [17] there are two types of cable ageing: intrinsic and extrinsic. Intrinsic ageing causes irreversible changes in the insulation material properties. It may affect a large volume of insulation and occurs, for example, when ageing factors interact with contaminants (Eg: x). Extrinsic ageing results in localized changes of an otherwise uniform material structure. This kind of ageing usually begins in localized regions and gradually propagates through the insulation (maybe becoming intrinsic) [17].

In the following table (Table 3.2) are the factors that affect cable insulation ageing, acting singly or synergistically [17].Note that the effects of ageing mechanisms may lead to different failure mechanisms. For example, thermal cycling may cause loss of adhesion (mechanical) [17]. The failure mechanism is usually electrical, e.g., by PD, ET or tracking [17].

In the Annex A.1 , there are two tables (Table A.1 and A.2) that summarize the diagnostic ageing tests, including their advantages and limitations, used for oil-filled and extruded cables, respectively. These tests will help utilities to assess their asset's condition – ageing or damage extent.

According to [17, 53] fluid-filled systems are mostly affected by thermal ageing, because of the increased chemical reaction rate at high temperatures. This degradation with temperature follows the Arrhenius law, according to which de degradation rate doubles every 8-10^{o}C rise in temperature, considering an 80-110^{o}C range. However significant thermal ageing does not necessarily mean the failure is imminent, unless the cables are subjected to any unusually extreme conditions. In this case the failure will be imminent. Another important degradation factor is when moister comes into contact with the paper [17]. This can happen with paper hydrolysis, incomplete cable drying or through leaking or corrosion, cracks or faulty seals. When water comes into contact with paper/oil the insulation's dielectric loss increase. This can even cause thermal ageing because of dielectric heating or even failure due to thermal runaway. This kind of degradation can in some cases, cause rapid cable failure (within weeks of the moisture getting absorbed by the insulation). Electrical stress is reported to not have any effect on thermal ageing of oil/paper cables, given that there are no **PD** (**Partial Discharges**) [17].

The main ageing factors for extruded cable systems are electrical mechanisms, bthe most common being: PD, **Electrical Treeing** (**ET**), **Water Treeing** (**WT**) and charge injection – occur at **contaminants, defects, protruisions and voids** (**CDPV**). These ageing mechanisms tend to be localized [17]. There has been a focus on eliminating CDPV and despite their reduction, it just is not possible to eliminate them completely. They are especially significant in accessory ageing, particularly joints and terminations, that makes accessories more vulnerable [17].

Table 3.2: Ageing factors that affect cable insulation systems [17]

Ageing factor		Ageing mechanism	Effects
Thermal	High temperature Temperature cycling	- Chemical reaction - Incompatability of materials - Thermal expansion - Diffusion - Anneal locked-in mechanical stresses - Melting/flow of insulation	- Hardening, Softening, Loss of mechanical strength, embrittlement; - Increase tan delta; - Shrinkage, loss of adhesion, separation, delamination at interfaces; - Swelling; - Loss of liquids, gases; - Conductor penetration; - Rotation of cable; - Formation of soft spots, wrinkles; - Increase migration of c omponents.
	Low temperature	- Cracking - Thermal contraction	- Shrinkage, loss of adhesion, separation, delamination at interfaces; - Loss/ingress of liquids, gases; - Movement of joints, terminations.
Electrical	Voltage (ac,dc, impulse)	- Partial Discharges (PD): - Electrical Treeing (ET): - Water Treeing (WT); - Dielectric losses a nd capacitance; - Charge injection; - Intrinsic breakdown.	- Erosion of insulation (due to ET); - PD; - Increased losses and ET; - Increased temperature, thermal ageing, thermal runaway; - Immediate failure
	Current	- Overheating	- Increased temperature, thermal ageing, thermal runaway.
Mechanical	Tensile, compressive, shear stresses , fatigue, cyclic bending, vibration	- Yielding of materials; - Cracking; - Rupture.	- Mechanical rupture; - Loss of adhesion, separation, delamination at interfaces; - Loss/ingress of liquids, gases.
Environmental	Water/humidity Liquids/gases Contamination	- Dielectric losses and capacitance; - Electrical tracking; - Water treeing; - Corrosion.	- Increased temperature, thermal ageing, t hermal runaway; - Increased losses and ET; - Flashover.
	Radiation		Hardening, softening, loss of mechanical strength, embrittlement

3.2.3 Soil thermal resistivity and underground cables

As mentioned in Section 3.1.2 cables are mostly directly buried in the ground, so the fill over the cable must be chosen according to its thermal resistance properties (low resistivity is desired). When electricity is flowing in a conductor it generates heat. A resistance to heat flow between the cable and the ambient environment causes the cable temperature to rise. Moderate increases in temperature are within the range for which the cable was designed, but temperatures above the design temperature shorten cable life [7]. Soil is between the heat flow path of the cable and the ambient environment, and therefore presents its self as a thermal resistance. So, the soil thermal properties must be taken into account in the overall cable installation design [7, 11, 54].

According to existing resistivity models there are five constituents that determine the soil's thermal resistivity: quartz, other soil minerals, water, organic matter and air (ordered according to increasing resistivity) [7].

As stated by [7] five soil and material factors have to be taken into account when choosing the cable soil fill:

1. Air is bad, so soil must be tightly packed to minimize air space and reduce thermal resistance;

2. Replacing air with water helps, even though water is not the most desirable conductor;

3. Organic matter, even wet, has a very high resistivity;

4. Fill material must be ideally filled with quartz or similar material, as it has the lowest resistivity.

As the figure below shows (Figure 3.8) a higher thermal resistance is associated with higher density, and as mentioned above, quartz is the ideal fill.

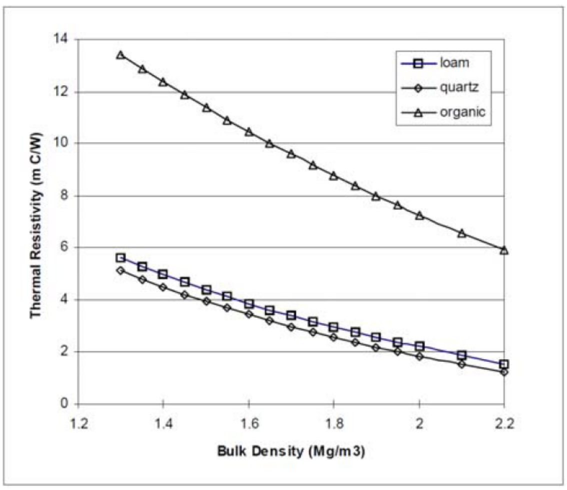


Figure 3.8: Thermal resistivity variation with bulk density [7]

It is not only the soil type that has an impact on soil thermal resistivity, but also the grain size [54]. The bigger the grain, the more air exists in the soil and the higher the thermal resistivity. For this reason, as mentioned in Chapter 3.1.2, a layer of sand if put over the cables, due to the small grain size that reduces the air between grains [5].

In some cases, pore spaces in the soil are filled with water rather that air, as it lowers the resistivity [7]. The figure below (Figure 3.9) shows the effect of water on the different soil types.

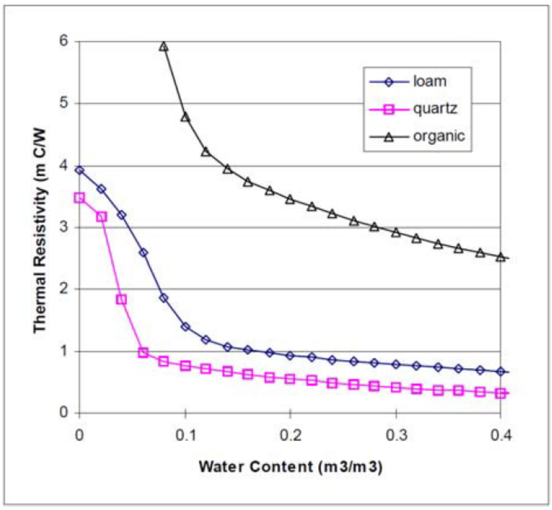


Figure 3.9: Thermal resistivity variation with bulk density [7]

The depth at which a cable is buried also affect the thermal stability, as the deeper the cable is buried, the more stable the thermal environment – less thermal variation. This happens because the thermal variation is lower, because there is a lower energy exchange between the air/ambient and the soil. But the deeper the higher the costs.

Along the cable route, there are the so called ‘hot spots’, that should be monitored, because they can cause premature cable failure, as explained at the beginning of this chapter. Theses hot spots are due to drained soils or vegetated areas, both responsible for drying the soil, thus increasing the thermal resistivity [7].

3.3 Electricity utilities’ experience with underground cables

3.3.1 The importance of proper data acquisition

Currently utilities are experiencing some information gaps regarding historical cable information, like age-related failure information (age of failed cables) and cable type failure information (Eg: unknown cable types) [15]. In other words, in the past there has been a general neglect or deficient information of underground failures, making it hard to currently identify influencing factors on aging network components (including underground cables)[15]. This information gap is not the same for every electricity utility, some have already introduced changes in their data acquisition scheme and have access to more information. The general direction is to list as much information as possible about failures that occur (age, cause, equipment condition, etc). It must be added that not all of the power system's factors are practical for monitoring [15, 55].

Mathematical models have been developed to deal with the kind of information available, in order to either extract information or perform predictions to help maintenance decision, for example. These models and how they fit in maintenance or asset management decision will be discussed in Chapter 3.3.3.

The authors in [15] describe a data acquisition scheme used in Germany that is a result of several years of process development. This database is a result of joint work by network operators, to gather as much detailed information as possible. Based on this an ideal data base consists of five data set blocks [15]:

- Identification of the damage event: data, number;
- Information on the subsystem containing the faulty or damaged component: identifier, type of insulation, voltage level;
- Information on the damaged/faulty component: year of manufacturing, technology, manufacturer, installation year;
- Description of damage/fault details: cause, occasion, maintenance measures, damage potential costs;
- Description of network failure if relevant: condition, duration, affected clients, type of failure;

In order to avoid inefficient or faulty entries, most of the data fields should be implemented as list boxes. There has been an increase in the level of detail when comparing to previous data acquisitions.

3.3.2 Operational and lab testing experience: failure rates and ageing/deterioration

As result of cable evolution, it is expected that utilities possess a mixed underground network, both dry and fluid-filled cables. It is expected that by now utilities have substituted a large percentage of their fluid-filled cables, remaining only the ones that have not failed or needed substitution so far [5, 8, 10]. This section will discuss the concern with mixed cable systems, experienced underground failure rates and cable ageing and deterioration phenomena.

Currently, cable substitution is commonly carried out using the most recent technology. For example, whenever fluid-filled cables need changing, they are substituted by the dry-cured cables, because of their proven higher performance, in particular the tree-retardant XLPE cables [56, 57].

The main concern regarding utility service experience with mixed cable MV network is how the various technologies influence the cable or underground failure rates. A study [8] was conducted in Denmark and has shown that there are some indications that failure rates for PILC cables in mixed cable systems are higher than in pure PILC cable systems. But this observation is drawn with some reservations, as the exact numbers of the cables in the mixed cable system are not known. This is a consequence of the evolution of the data acquisition process over the years, mentioned in Chapter 3.3.1. The study also calls the attention for cable accessory failure, as the overall cable system failure rate also depends on cable accessories [8]. In the figure below (Figure 3.10) a graph with the cable and accessories' failures between 1999 and 2009 .This information was based on the Danish failure and interruption database [8].

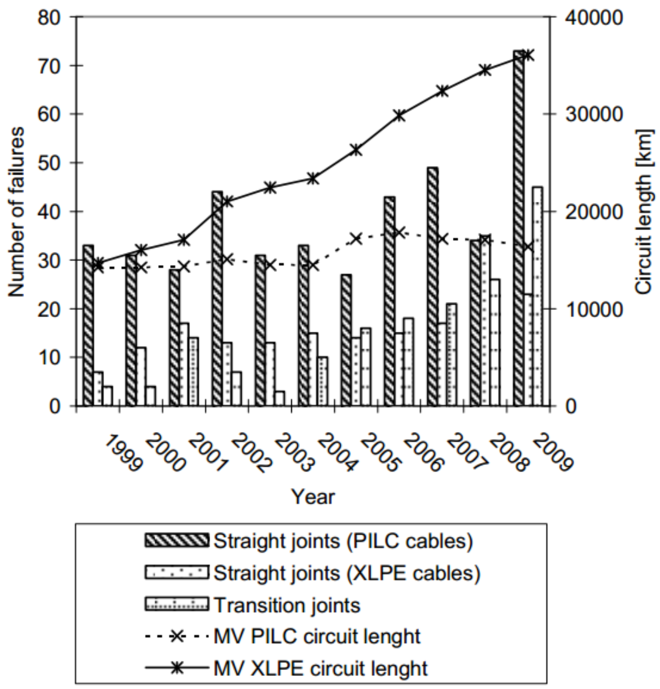


Figure 3.10: Failed MV cable joints between 1999 and 2009 [8]

As the figure shows (Figure 3.10) an increase in MV XLPE cables and a decrease in PILC cables (as expected). the higher number of failures of the accessories is in PILC cable joints, that represent 12% of the known cable joint types, so this is a high failure rate for a small percentage of accessories [8]. But there is a large percentage (52%) of unknown joint design. Regarding failure causes, ageing is the number one cause. So, following the study's uncovered that there seems to be an influence of the older technologies in the mixed system that inflates the general system's failure rate. This information can be used for making maintenance and reinvestment decisions, balancing variables of the replacement costs and what an acceptable failure rate is for a particular mixed cable system [8].

There has been a rises in concern and observation of cable ageing or service-ageing, which has become a recurring theme for cables and cable accessories [9, 10, 58, 59, 60]. The main ageing mechanisms and diagnostic tests are discussed in Chapter 3.2.2.

Ageing can occur naturally or in an accelerated manner. As mentioned in Chapter 3.2.2 when cables experience a variable operation state, they can suffer from accelerated ageing or deterioration. This variable operation is a result of a new power system paradigm, mainly because of renewable energy penetration, which is known for its variability [15]. A correlation has been established between accelerated ageing phenomena and long-term cable performance [58]. Lab trials have been executed, allowing poor performing materials to be differentiated from those with superior performance (dry-cables), correlating the results to life expectancy. Testing was done following an ACLT protocol that mimics real-world ageing mechanisms for cables in service [58]. Getting this information from on site and in service cables is costly, and normalized lab studies have proven a good approximation at a lower cost. Understanding the ageing phenomena has proven useful for developing cable failure prediction models, which will be further discussed in Chapter 3.4.

The figure below (Figure 3.11) represents the number of failures for cables with known installation year [9]. It is possible to observe that older cables are responsible for most of the recent registered failures, thus emphasizing the ageing phenomena in underground power cable systems.

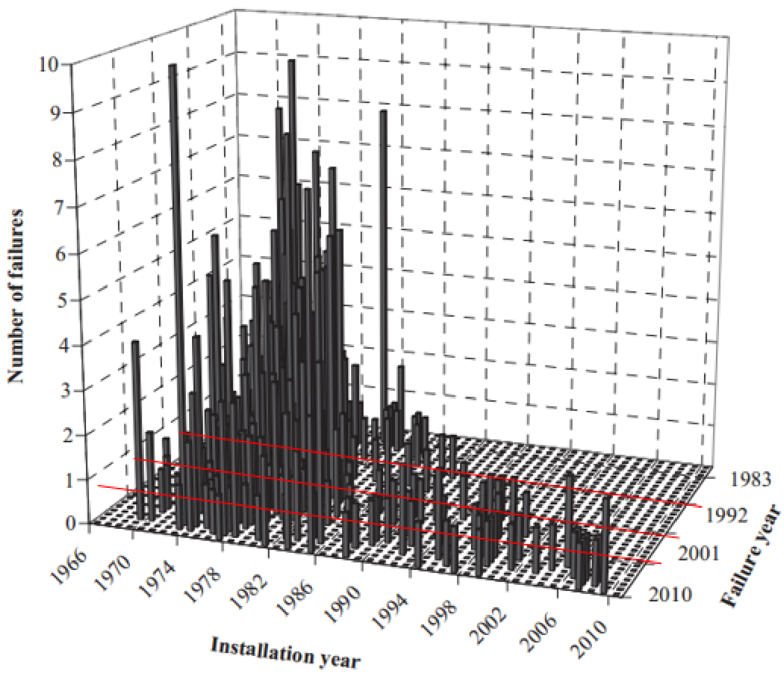


Figure 3.11: Registered failed cables with known installation year [9]

Failure rates can be determined considering or not service time (cable age), which depends on the available information (See Chapter 3.3.1). The following mathematical expressions indicate how to calculate for each scenario the cable failure rate, that is represented by . Not considering cable age [61]:

$$\lambda = \frac{N^o failures}{N^o components/length \times N^o years}[n^o Incidents/km/year] \tag{3.1}$$

Considering cable service time [9]:

$$\lambda_h = \frac{\sum^i \sum^h N_{i,h}}{\sum^i \sum^h L_{i,h}} \tag{3.2}$$

where:

$N_{i,j}$ - Number of failures in year i on cables with service time h;

λ_h - Failure rate for cables with service time h.

It is expected that failure rates will be higher with time, if cable substitution or maintenance is not considered.

3.3.3 Seasonal behaviour and cable failures

Some utilities have perceived that there is a relationship between cable failure and seasons [10, 11, 54]. The figure below (Figure 3.12) is a seasonal cable incident plot. There is an observable increase in the number of incidents in summer months that are associated to higher temperatures and generally drier weather (and soil).

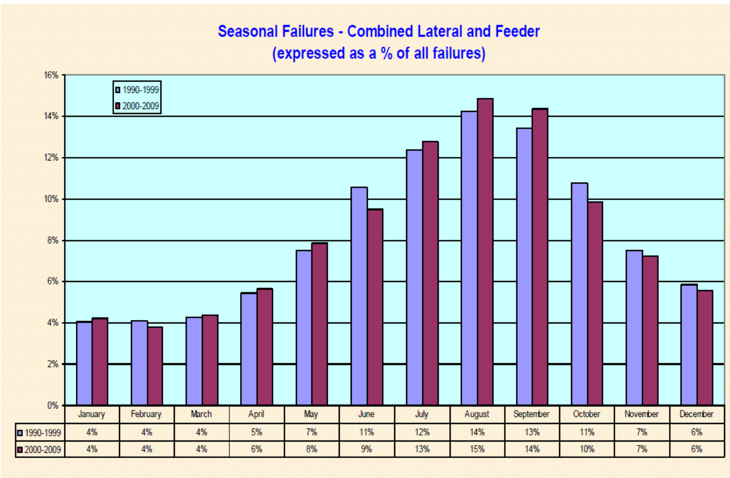


Figure 3.12: Seasonal behavior of cable incidents [10]

After investigating the relation between ambient temperature and the number of failures, [11] determined a correlation between them, considering 2 approaches:

1. Direct correlation between temperature rise and failures;

2. Considering a delay in the temperature's effect on the number of cable incidents.

Figure 3.13 is plot of the average temperatures and cable incidents during 2002-2006. The linear correlation coefficient (also known as Spearman's coefficient) for July and August was about 0.88 (the maximum is 1), a high positive correlation that means that there is a strong positive (both variables increase or decrease) correlation between the temperature increase and the increase in the number of cable incidents.

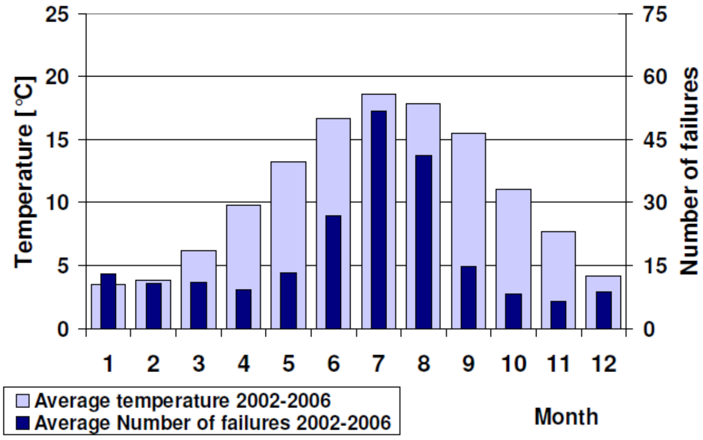


Figure 3.13: Average ambient temperature per month and average number of failures in the period 2002-2006 [11]

It is also possible to take into account the soil heating and cable incidents occurring with a certain delay due to temperature rise [11, 54] - considering the soil temperature model developed in the paper [11]. The figure below shows the correlation coefficient when considering a 0-6 delay, the red line being the critical correlation value. The values in this case are only for the year 2006, where the Netherlands experienced higher temperatures in July and August [11]. It is observable that a 2 to 3 day delay in the temperature effect gives a higher correlation coefficient with the cable failure, suggesting that the effects of temperature on cable failure are not immediate.

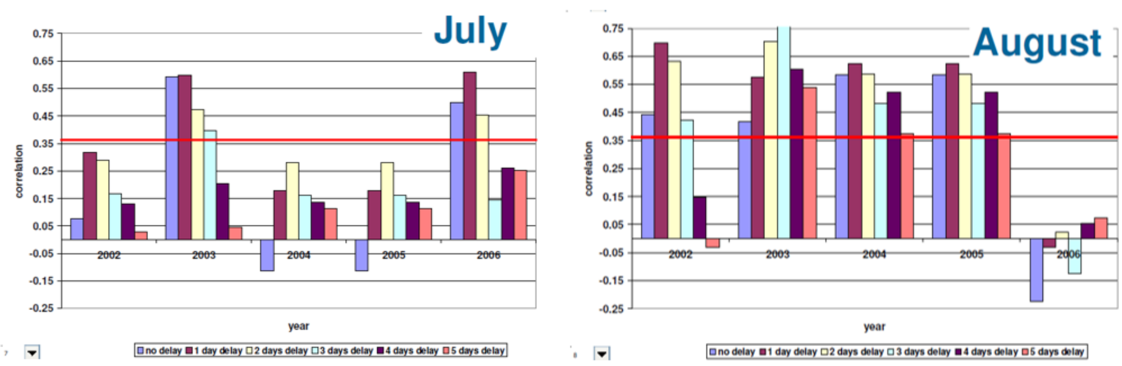


Figure 3.14: Correlation of the occurrence of failures and ambient temperature including a delay of 0-6 days, the line shows the critical correlation value [11]

3.4 Underground network reliability and asset management

3.4.1 Distribution Asset Management (AM)

Asset management (AM) has become increasingly popular in distribution utilities, mainly because of the network's dimensions, as it consists of numerous and expensive components [13]. AM is a *"corporate strategy that seeks to balance performance, cost and risk"* [12]. The main goals of AM are to [12]:

- Balance cost, reliability and risk;
- Align corporate objectives with spending decisions;
- Create a multi-year asset plan on a rigorous and data-driven processes.

There are three pillars of competency that support AM – Management, Engineering and Information – that are represent in the figure below (Figure 3.15). Usually projects or initiatives, within a utility, regarding AM are led by a project manager, but supported by departments or people with knowledge in the full length of issues related to AM. Otherwise, projects will only achieve tactical goals, compromising the overall AM strategy [12].

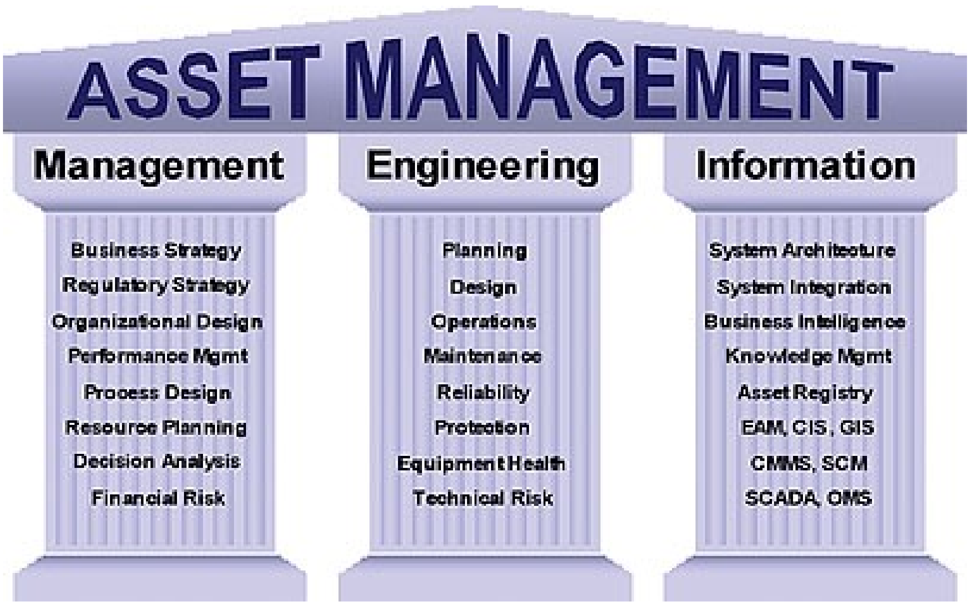


Figure 3.15: Asset Management pillars of competency [12]

The diagram below (Figure 3.16) illustrate the AM decision scheme within which three processes can be distinguished: Maintenance, Modifications and Investments [13].

All the aspects mentioned in Chapter 3.3, regarding cable condition, ageing and failure, are taken into accent in AM decisions, as utilities debate wither to refurbish, maintain or replace underground cables. This AM understanding serves as context of the utilities preoccupation with underground ageing and failing cables, as mentioned at the beginning of this chapter.

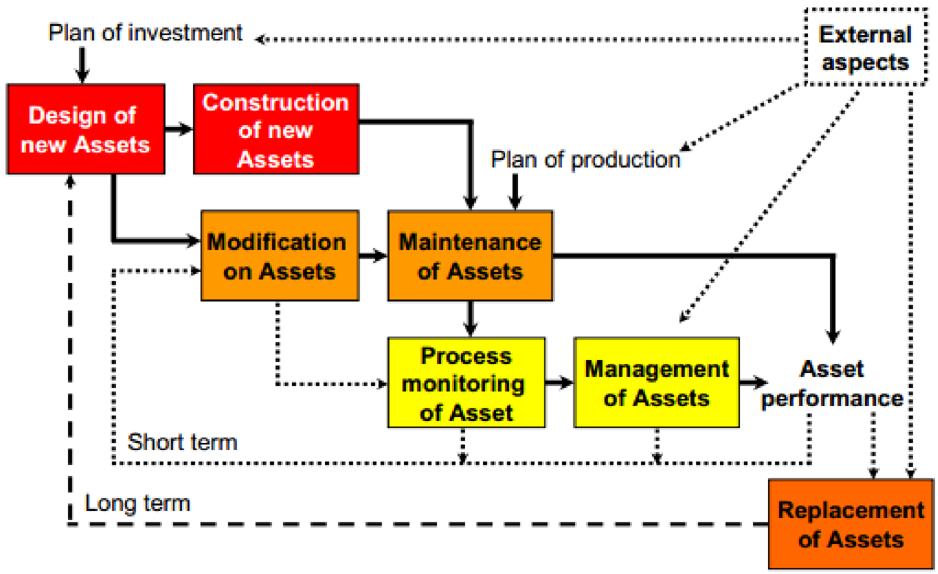


Figure 3.16: Asset management decision scheme [13].

3.4.2 Statistical life-time data analysis and reliability models

3.4.2.1 General cable failure prediction model

The method described in this section is a statistical based model built using life data, which includes cable age and failures information.

Dispersion of data is common in cable life data or failures [14]. This data can be evaluated using parametric or non-parametric methods. The model presented in this section is based on the parametric method, in which statistical distributions are used to fit the data and to estimate the distribution parameters, and which was based on [13, 14, 60, 62]. The figure below summarizes the steps in data collection, statistical analysis and prediction or decision support based on the statistical analysis (Figure 3.17). These steps will be discussed in more detail below.

Life data always results in an estimate, as the true value for the failure probability, reliability and distribution parameters are never known. But with a statistical analysis an estimate of the true values can found with certain accuracy/confidence [14].

1. Data collection [13, 14, 59, 60, 62]

The first step is the data collection, without which the analysis is not possible and from which information about the system is extracted. As mentioned in Chapter 3.3.1, it is important to have proper system data collection. This allows operators to analyse the system's condition and to predict trends, that will help making AM decisions [13, 14]. The more information about the system and is occurrences, the stronger the conclusions. This data can range from in-service data

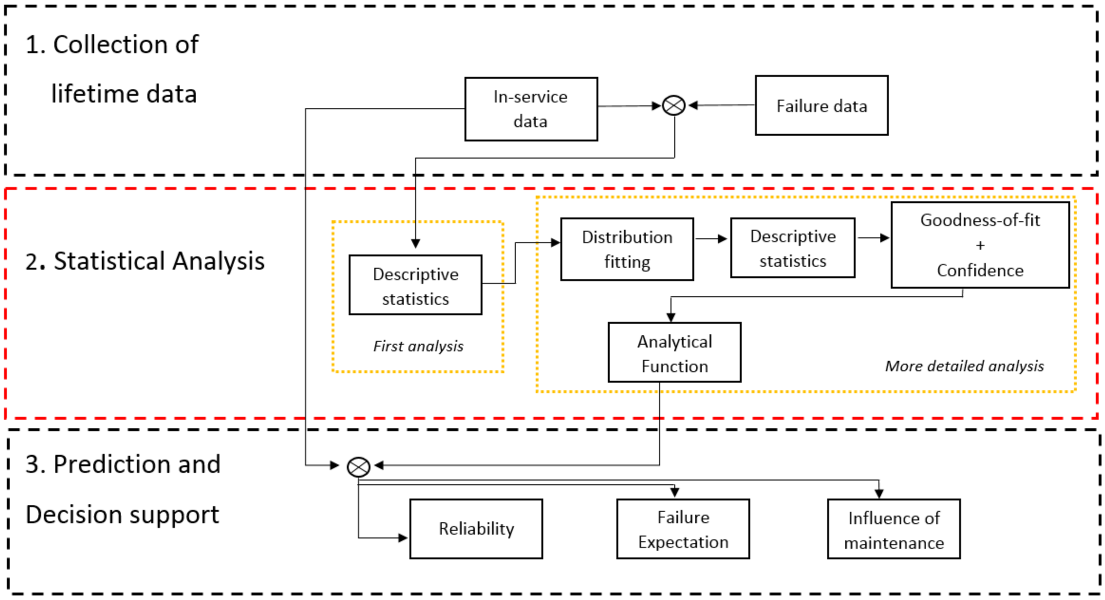


Figure 3.17: Steps for performing statistical analysis and prediction on data, based on [13, 14]

(component condition), failure data and other relevant data like soil type, ambient temperature, etc.

2. Statistical analysis [13, 14, 59, 60, 62]

After the data collection a statistical analysis can be performed and it is basically performed in 5 steps:

- Step 1: Descriptive analysis (first analysis);
- Step 2: Distribution fitting;
- Step 3: Distribution parameter estimation;
- Step 4: Goodness-of-fit test;
- Step 5: Confidence bounds (**CI – Confidence Intervals**).

Methods of descriptive statistics, such as histograms and polygons of cumulative function of occurrence, are applied to get the first impression of the failure behaviour.

Distribution fitting is determining which distribution is more appropriate for the data points from the collected data. This can be done by performing the fitting of different distributions. The horizontal axis represents the failure time, age or diagnostic parameters of the component and the vertical axis represents the unreliability in percentage. The unreliability is described (see expression below) by a **cumulative distribution function** (**CDF**) that gives the probability that

"X" (Eg: Component) will be at most at a certain value "x" (Eg: Component survival time, also known as "t").

$$Q(t) = 1 - R(t) \tag{3.3}$$

$$Q(t) = \int_0^t f(s)ds \tag{3.4}$$

$$\frac{dR(t)}{dt} = -f(t) \tag{3.5}$$

where:

$Q(t)$ - Unrealiability;

t - Failure time;

$R(t)$ - Reliability.

After choosing the distribution that fits the data, the respective parameters have to be estimated. There are several methods for parameter estimation. They can be obtained from the plot of the fitted CDF. Other methods that can be used are the Least Squares Estimation and the **Maximum Likelihood Estimation** (**MLE**) . The estimation method depends on the data being analysed.

After choosing the distribution and estimating its parameters, the goodness-of-fit test is used to determine how well the chosen distribution fits the data points. Basically the procedure involves calculating the CDF of the tested distribution with the **Empirical Density Function** (**EDF**) of the data set. In other words, it compares the theoretical model with with the real world or data set model.

The test results can be used to compare the fit of different distribution used on the data, so that the best fitting distribution is selected. This comparison can be done using the available **goodness-of-fit tests**. The Least Squares Estimation is used to determine a correlation coefficient that describes the distance between the data points and the fitted distribution. Other commonly used tests are the **Kolmogorov-Smirnov**, **Chi-squared** and **Anderson-Darling tests**. Visual verification is also important when choosing the best fitting distribution. The amount of available data determines the statistical precision of the fitted distribution and is defined by the called **Confidence Bounds** or **Confidence Intervals** (**CB** or **CI**). These indicate the repeatability of the parameter estimation in many sampling trials. This is performed after the goodness-of-fit test.

3. Prediction and decision support [13, 14, 59, 60, 62]

Based on the statistical analysis of life data, future failure behaviour of components can be estimated. Usually this is called in papers as *"decision support"* and can considered replacement strategies.

The reliability evaluation determines if the population or part of it (sample) can fulfil the requested reliability by the asset manager. This is evaluation is done using the called B-lives, which are based on the fitted CDF and the component's age. The B-lives indicate the reliability level based on the component's age. In practice the B10 is an accepted value, which means that 10% of the total population will fail, at a certain age or parameter value, and 90% survives. Different values can be used depending on the acceptable unreliability/reliability, that is also dependant on the critically of the component's failure. When the probability gets too high, the component with the highest age of the chosen B-life can maintained or replaced.

Based on the fitted distribution failure rate and the population in service, an expected failure rate for the upcoming years can be calculated. The estimated failures of the past years can be compared the occurred failures, in order to see if they are comparable. The expected number of failures is calculated in the following way:

$$N_{f,e} = \sum_{i=0}^{AgeOldest} \lambda(t_i).N_i \tag{3.6}$$

where:

N_i - Number of joints with age i in-service;

$\lambda(t_i)$ - failure rate at age i.

This analysis gives insight on what the failure's development will be in the upcoming years. Different confidence bounds can be applied to observe the variety of outcomes.

Further analysis can be given when combining the failure rates with component replacement strategies, see [14].

3.4.2.2 Comprehensive damage statistics in distribution systems

This section will present the model proposed in the paper [15] for evaluating component condition and reliability in MV distribution systems. This model was developed because of the fluctuating electrical stresses demanded an improvement for modelling component reliability and to determine the resulting quality of supply. This model's goal was to develop the base for well-founded input for AM processes. So the impact of present decisions on the development of quality of service need to be estimated as exactly as possible, particularly due to quality of service incentive regulation.

The aim of this model is a type-specific prognosis models based on empirically determined characteristics of age-related damage frequencies.

The damage data was provided is checked for plausibility before being used for modelling. The proven data, the component quality structure and the information on maintenance are combined, thus calculating the empirical damage frequency (h_s) using the formula bellow:

$$h_s = \frac{N_s}{M_s.T_B} \tag{3.7}$$

Where:
h_s - Empirical damage frequency;
N_s – Number of relevant events;
M_s – Component quantity;
T_B – Period under consideration (usually 1 year)

Depending on the type of component Ms can correspond to a number or a length. The frequency can be calculated for different criteria, like component age, maintenance cycles, type of technology and others.

The component's behaviour simulation is done by superposition of four basic functions to one model function as shown in Figure 3.18. The empirically determined frequencies serve as input data for the parametrisation of the model function, in order to find the best combination of basic functions with the minimal deviation from the input data.

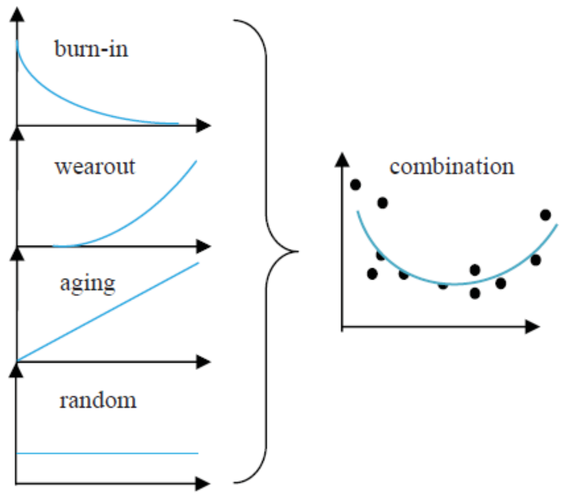


Figure 3.18: Basic functions and model function for modelling component reliability [15]

The basic functions mentioned above represent typical phenomena that influences component condition and are expressed by the following equations:

$$h_{burn-in}(t) = b_1.e^{-b_2.t} \tag{3.8}$$

$$h_{wearout}(t) = b_3.(e^{-b_4.t} - 1) \tag{3.9}$$

$$h_{ageing}(t) = b_5.t \tag{3.10}$$

$$h_{random}(t) = b_6 \tag{3.11}$$

$$h_{combination}(t) = b_1.e^{-b_2.t} + b_3.(e^{-b_4.t} - 1) + b_5.t + b_6 \tag{3.12}$$

The estimation of the distribution parameters is based on the non-linear Least Squares method and the Levenberg-Marquard-Algorithm is used as the numerical solution for the problem due to it stability and fast convergence.

The results of the investigation are published in the paper [15]. The conclusions are that this model, with the right amount of information, allows to achieve a well-funded information on the conditions and ageing behavior of network components. This is specially usefull in MV systems, as it allows statistical analysis combined with sophisticated approaches to provide additional knowledge, as individual condition assessment and monitoring systems require too much effort. The results of the investigation allow the evaluation of the supply reliability for different maintenance and renewal strategies and that can be suited in quality of service indexes like SAIDI and SAIFI. The determined frequencies of damage events and the described extension in the network failures close a gap in existing AM procedures. Additionally this model can provide indications of weak spots of components and the effectiveness of corrective procedures.

3.4.2.3 Probabilistic underground cable failure and replacement strategies

This section will present the model proposed in the paper [55] that proposes a parametric model for short term failure and the formulation of replacement strategies, using the Monte Carlo simulations to determine confidence bounds of forecasted component performance data.

The data used in this model contain the most salient features known to be a strong determinants of the component's lifetime. This data is assumed to be consistent with the Weibull distribution, due to its degree of flexibility, when compared to other distributions. Ideally large amount of information should be available in order to build accurate statistical models. But, in most the cases only partial information is available (See more in Chapter 3.3.1). For this model the database is considered to contain the following information: year of installation, number of components replaced in any given year and the total number of failures in any given year. It is no assumed to be known the age of the failed components, *"as such statistics are rarely known in utilities"*.

Basically this model considers the following steps:

1. Real data failure rate;

2. Estimated failures without cable replacement;

3. Estimated failures with cable replacement;

4. Monte Carlo failure simulation for confidence bounds.

The results show that the algorithm can be used to forecast how present actions affect the overall failure trend. This algorithm can be altered to include data obtained through condition monitoring to increase the accuracy of the results.

The Monte Carlo simulation was employed to extract the confidence rang of the estimated failure rates or the replacement rates needed to maintain the desired failure performance.

3.5 Importance of this chapter for the work developed in this thesis

This chapter aims to summarize utility experience with cable failures, factors taken in to account for cable manufacturing and cable deterioration factors. These are important because they help to increase the understanding of cable failure behaviour, which allows the network operators to make maintenance decisions. This chapter summarizes utility experiences, which is important for getting an understanding/picture of what studies and conclusions are currently accepted/verified.

In order to conduct cable failure studies and statistic analysis, the information needs to exist. A problem which lots of utilities are faced today is that they have insufficient or faulty information on cable failures, especially cable age. Utilities are also faced with an ageing underground network, which is a result of actually old cables (service years longer that 40) and also an accelerated cable ageing. So this increases the need to understand and predict cable failure in order to make maintenance decisions, in asset management. Another factor besides ageing is the existences of mixed cable networks, which reflects cable evolution, as nowadays oil filled cables are being replacement by dry/extruded cables with higher performance. It is important to understand the overall network behaviour and to determine if it is not being inflated by the oil filled cables.

All the problems, approaches and solutions obtained by utilities will be taken into account when analyzing the failure data from the Portuguese MV underground network. The objective will be to compare the studied network behaviour with observations on cable failure behaviour by other utilities, in order to test existing theories and conclusions.

The next chapter will present the developed work and results of this thesis (Chapter 4).

Chapter 4

Portuguese distribution MV network characteristics and cable behaviour

The objective of this work is to determine the MV underground cable's behaviour, which could be the basis for future developments in the area in Portugal. For this reason the work was divided into five phases: existing approaches and applicable regulation, data acquisition and treatment; data analysis; statistical analysis and improvements/suggestion of future work.

4.1 Introduction and methodology

In this chapter all the work **processes** and **results** will be presented, with explanations of the limitations, **assumptions** and used data. The work developed in this thesis is innovative in its area in Portugal, and the objective is to determine the Portuguese MV underground cable behavior, including verifying if there is any seasonal behaviour. The conclusions drawn can be used in asset management decisions in the distribution network.

For graphs and results the unit system used is the international S.I. unit system. Additionally not all the analysed information can be presented, in order to maintain confidentiality.

The work developed in this thesis was divided into five phases, as the figure below summarizes (Figure 4.1). Each phase requires a distinct methodology, discussed in sections 4.2, 4.3 and 4.4.

The **first** part represents the start of the work developed in this thesis and consists of researching existing literature and similar work in the area, as well as applicable regulations. As a result the chapters 2 and 3 were written, giving a context and summarizing existing work in the area of underground network failures. In terms of regulation only the RQS (discussed in Chapter 2) is applicable. There is also the **Guide for Incident Classification in the Distribution Network** (**GICDN**) [63], which is an internal *EDP Distribuição* document, that reflects the dispositions of the RQS. *EDP Distribuição* is the concessionary utility for energy distribution in continental Portugal and the mentioned guide indicates the procedures for incident registration. This first part was important as this work is innovative in its area in Portugal, so it was important to understanding existing approaches and conclusions.

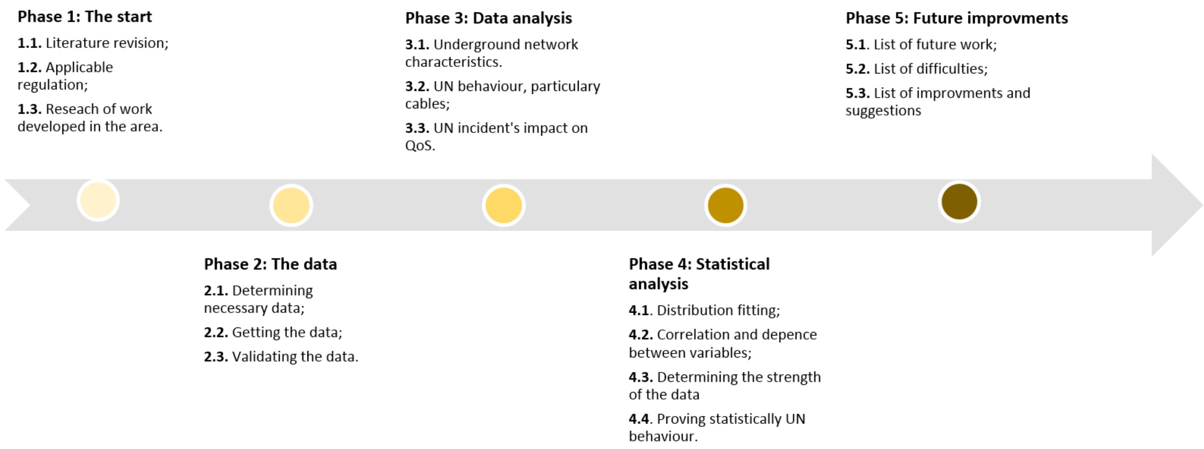


Figure 4.1: General work methodology: work phases

The data was identified and obtained using both information available in EDP's databases and external entities, like **IST** and **IPMA**. This **second** phase also includes data treatment and validation, to verify databases' conformity and also to guarantee compatibility between databases. In order to have easy to group information using the Pivot tables, the information needed to be organized accordingly.

The **third** part is the data analysis, which includes determining failure rates and summarizes the underground network behaviour, especially MV underground cable failure. This part also includes an analysis of the underground cable's impact on the overall MV underground network QoS.

The statistical analysis of the data – **fourth** phase - determines if there is any statistical relevance in the data for some observed behaviour, like cable failure seasonality and distribution fitting of variables.

The final part of this work consist of listing the main suggestions for improvement and future work for MV underground cable failure.

The figure below (Figure 4.2) summarizes the time spent in each work phase and shows that the data treatment was the most labour-intensive part, followed by the research.

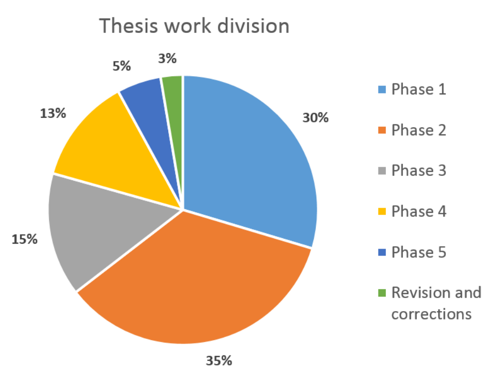


Figure 4.2: Overall work time distribution

4.2 MV cable failure data

4.2.1 Choosing data

This section explains how the necessary data was chosen and why, in order to determine MV underground network characteristics and study cable failures. The list of necessary data may not coincide with the actual acquired data.

To analyse MV underground network failure (particularly cable failure) the following information is necessary:

1. Incident[1] ID: an unique identifier of each incident;
2. Incident location: district, region, GPS coordinates;
3. Incident cause(s);
4. Incident duration;
5. Incident date and time;
6. Clients affected by the incident;
7. Power cut information (if existent);
8. Component age or installation date;
9. Component group: if the component is a cable, overhead line, accessory, etc;
10. Component type: in the case of cables if they are oil-filled or dry, in the case of accessories if they are joints, terminations or derivations;
11. Soil type for buried components (eg. Cables and accessories);
12. Temperature at failure time;
13. Weather at failure time;
14. Cable current at the time of failure (in Amperes - A);
15. Network length.

As mentioned in Section 3.3 component age may be missing information. If the utility is interested in determining cable age failure evolution, then the component age is an important parameter to consider. This may be interesting for planning component replacement and also identifying weak points in the distribution network, as older cables under varying operating conditions are more prone to failure because of the continuous subjection to ageing and deterioration mechanisms (Section 3.2.2 and 3.3.2).

The temperature and soil type at the time of the incident are important for determining, with rigor, if the incidents are related to temperature variation (seasonality or temperature amplitude) and if there is also a relation between temperature, soil type and incidents. Section 3.2.3 shows that certain soil characteristics are better for temperature dissipation. Also, the combination of cable use (which means an increase of temperature for higher use) can increase cable failure probability.

[1] Incident – Refers to an incident in the network, that may or not include component failure.

4.2.2 Data collection: information

After defining in the previous section the necessary data for the analysis and study, the data needed to be collected. Some information was available in *EDP Distribuição* databases and additional information needed to be collected from exterior sources.

The information available was obtained from the following sources:

- EDP Distribuição: incident database (**Rede Activa**), MV network characteristics database (**SIT**) and load/consumptions database (**SCADA GENESys**);
- IST: Temperature prediction database;
- IPMA: Climate bulletins and relevant meteorological events.

At *EDP Distribuição*, incident registration is done according to the **GICDN** [63], which is based on utility experience and indications in the RQS (see Section 2.3.5). After an incident occurs in the network two kinds of reports are registered: an automatic report [2] for SD incidents and a manual report for LD incidents. These reports include information about the incident like duration, affected clients, causes, location of the incident – district, **DRC** and **AO** (further explained in Section 4.3.2) - , network type (overhead or underground), equipment type (cable, accessories, transformers, etc.) and some observations which include extra information on the incident (e.g. Responsible technician, visual information on incident and extra information that cannot be included in the other parameters). These report also includes information as specified in Section 2.3.5. *Rede Activa* is EDP's incident database and **CRI** (**Consulting Registered Incidents**[3]) is the interface which allows to consult incident reports.

The information extraction (incidents) from **CRI** was done in two phases according to incident duration (LD and SD) of incidents from 2001 to 2013. This resulted in two incident lists, which were imported into Microsoft Excel format. But this data did not contain failed cable age information.

The network characteristics were extracted from **SIT** (**Sistem of Technical Information** [4]) that is the Distribution Network's equivalent to Google maps, which extracted the MV distribution network and MV joints, terminations and derivations into Microsoft Excel tables. Regarding the loads/use database this was obtained also in Excel format and was exported from **SCADA GENESys**.

The incident database did not include the temperature at the time of the incident, nor were there any available temperature measurements. So, as an alternative, daily temperature predictions were used. This information was obtained from **IST**'s (**Lisbon Institute of Technology**[5]) meteorological website [64], but the only available data was from the end of 2007 unitl 2013.

[2]Automatic report - sent directly from GENESys to *Rede Activa database*
[3]CRI - *Consulta de Registo de incidentes*
[4]SIT - Sistema de Informação Técnico
[5]IST - Instituto Superior Técnico de Lisboa

IPMA (Portuguese Meteorological Institute[6]) publishes every year and recently, every month, climatological bulletins [65], which contain climate summaries, main events like storms or droughts. This information can be useful to explain periods with higher or lower number of incidents in certain regions, due to mentioned phenomena.

The information gathered presented two main problems:

- Compatibility between databases;
- Database errors (eg. missing or incorrect information).

4.2.3 Data treatment process

Most of the information obtained was in Excel format, but was not organized and not filtered/validated. Some information was even organized in several different Excel tables due to the volume of information. So after gathering all the information, data treatment was the next step in order to validate the data and pass onto to the analysis steps (Sections 4.3 and 4.4).

As the incident registration report for LD incidents is filled out manually, there is a possibility for some mistakes, which needed to be filtered and corrected. There was knowledge of some typical errors, which was taken into consideration when analysing the data. For the loads only information from 2010 to 2013 was considered, due to an identified growth in the total number of incidents per year, which will be further discussed in Section 4.5.

A common practice in *EDP Distribuição* is to attribute codes to equipment types, incident causes and locations (e.g. DRCs and AOs), which make it easier to correct mistakes and also for merging data without keeping repeated information (this was the case for separate Excel sheets for the same information). The remaining information only needed to be formatted.

4.3 Data analysis: MV underground network behavior

4.3.1 Analysis methodology

After validating and organizing the data, (process explained in Section 4.2), the data analysis was divided in to four phases, represented in the figure below (Figure 4.3). The **first** part is a general understanding of how the MV underground network is organized and some relevant characteristics such as age and network concentration. The **second** part is a result of the underground failure analysis, divided into cable and accessory study. The cable analysis was done with more detail as cables are the focus of this work. The **third** part is a analysis on cable failure's impact on the overall MV underground network QoS indicators. Finally (**fourth** part) a study of seasonal behaviour and a comparison with temperature, load and soil type. In this part a linear correlation using Excel is done to show the interest of doing a more detailed statistical study in Section 4.4.3.

[6] IPMA - Instituto Português do Mar e da Atmosfera

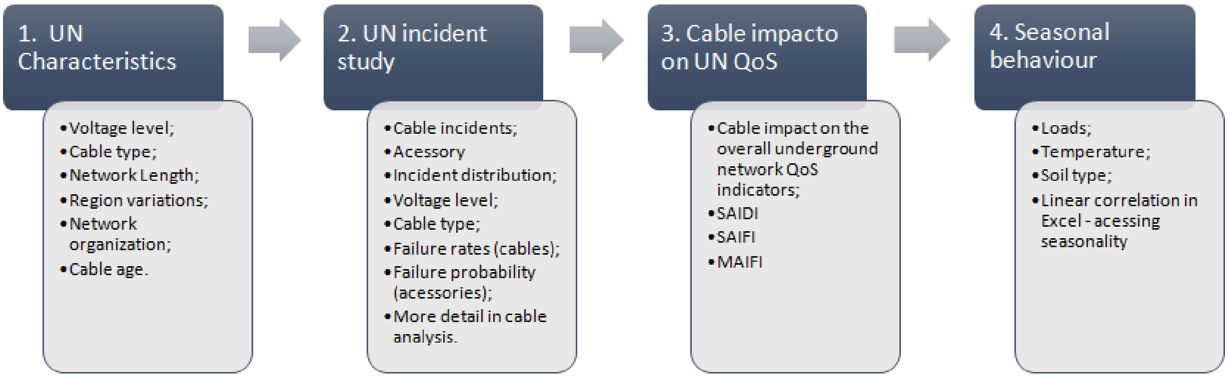


Figure 4.3: Methodology adopted for the data analysis

4.3.2 MV underground network organization and characteristics

The information in this section is based on the underground network database (from SIT).

The Portuguese MV underground distribution network is organized, according to EDP, in **DRC**s (**Client and Network Directions**) and **AO**s (**Operational Areas**), as the figure below shows (Figure 4.4 a). The AOs do not necessarily correspond to districts, so the same district (Figure 4.4 b) can belong to several AOs.

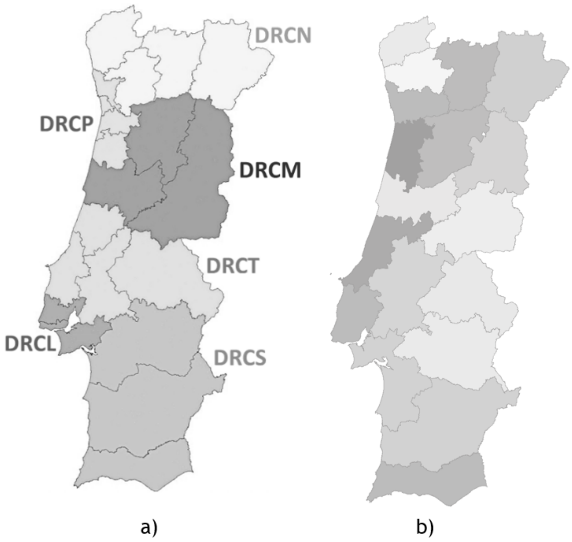


Figure 4.4: Network division in continental Portugal

The MV network is mostly overhead (81%) and only **19%** is **underground** (Figure 4.5), which is the focus of the work in this thesis. Regarding network distribution, as the Figure 4.6 shows, there is a higher **concentration** of MV underground network in more developed, cosmopolitan and urban centres (marked with red circles), as was expected. This has to do with the fact that in urban areas there is a constant need for space and overhead cables are not a good solution.

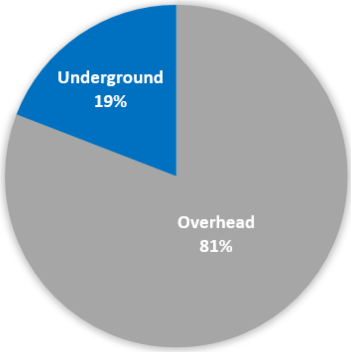


Figure 4.5: Cable type division

Over the years, as mentioned in Section 3.1.1, oil cables are becoming fewer as dry cables are replacing then, which is demonstrated by the figure below (Figure 4.7). As the figure 4.8 shows, there is a significant lower length of oil cables being installed over the years. Currently dry or extruded cables constitute a larger percentage of the MV underground network (Figure 4.7).

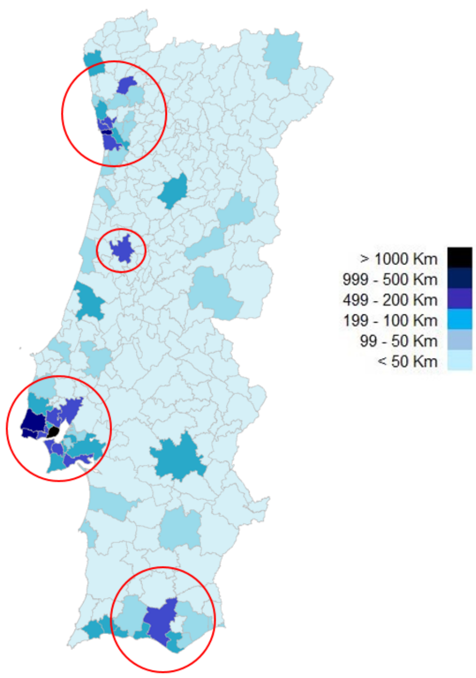


Figure 4.6: Cable length distribution

The MV underground network in Portugal is divided into 4 **voltage levels**: 6kV, 10kV, 15kV and 30kV. The figure 4.9, shows the percentage of the network that belongs to each voltage level. The 6kV network is an older and almost extinct network, as it is being substituted by other voltage levels. More than 50% of underground network's cable are 15kV and this is also true for both oil and dry cables . There is a higher percentage of 10kV among oil cables than dry cables, which is explained by the 10kV and the oil cable networks being older. The variety of voltage levels has to do with the network history, which is that EDP is the result of the merger of several energy companies with different network strategies. It is not economically and physically viable to replace all cables for a single type and voltage level.

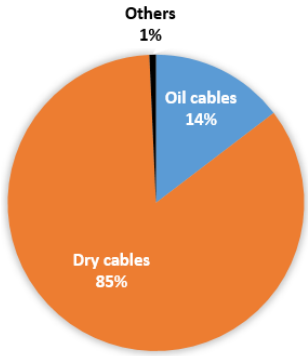


Figure 4.7: Cable type division

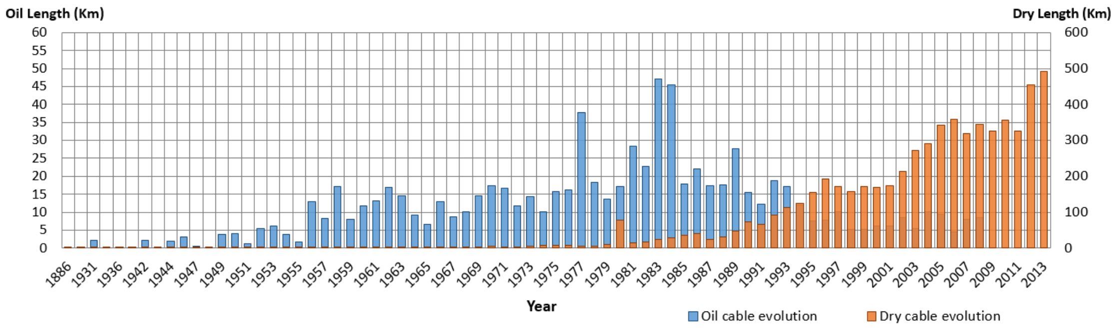
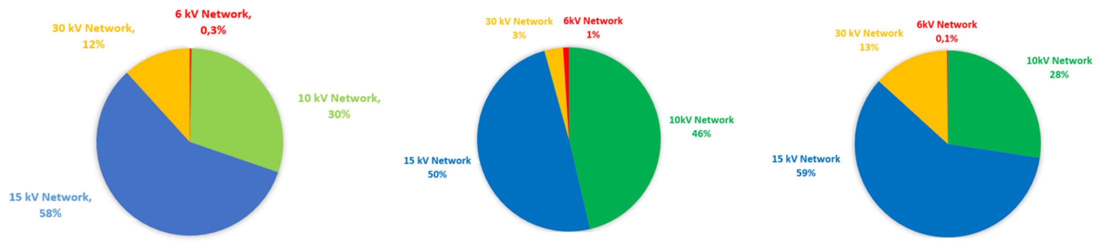


Figure 4.8: Cable length evolution: cable technology comparison



(a) General network voltage level distribution (b) Oil cable network voltage distribution (c) Dry cable network voltage distribution

Figure 4.9: MV Network voltage levels

In relation to the MV underground network's **age**, the table below summarize this information (Table 4.1). The percentages shown are in relation to the network length. The overall MV underground network age is young, mostly between the ages of 11-20 years. Dry cables' ages are mostly this ages or younger (10 years) which is the result of cable replacements in the network. As expected, oil cables are older, with the majority of cables being somewhere between 21 and 30 years old. Cables are expected to have a rather long life-time. For example, 4% of oil filled cables are more than 51 years old. The resemblances between the overall network age and the dry cables age is explained by the fact that this kind of cable technology represents 85% of the network (see Figure 4.7).

Table 4.1: MV underground network ages

Age bins (years)	MV UN (%)	Oil Cables (%)	Dry Cables (%)
$\leq$ 10	29 %	3%	34%
[11-20]	50%	6%	57%
[21-30]	14%	72%	4%
[31-40]	5%	9%	4%
[41-50]	1%	6%	0,2%
[51-60]	1%	3%	0,2%
>60	0,1%	1%	

In terms of **cable age** per **voltage leve**, the table below (Table 4.2) summarizes their ages. As expected the 6kV is an older network, but is not significant as it only accounts for 0,03% of the total MV underground network length (See figure 4.9a). Most of the networks are between 11-20 years, which is underground network's age. The 30kV network is the youngest, as 89% is under 21 year sand the remaining networks have cables with a wider range of ages (between under 10 and 30 years old). The 15kV network can be considered as the oldest, as it has the highest percentage of cables older than 41 (3,3%).

Table 4.2: MV underground network voltage level ages

Age bin (years)	6kV Network	10kV Network	15kV Network	30kV Network
$\leq$ 10	21%	20%	31%	42%
[11-20]	19%	57%	47%	47%
[21-30]	54%	22%	11%	8%
[31-40]	6%	0,2%	8%	3%
[41-50]	0%	0,04%	2%	0,3%
[51-60]	0%	0,03%	1%	0,2%
>60	0%	0%	0,03%	

This study was **important** to identify network characteristics and organization, which can be taken into account when trying to understand cable behaviour.

4.3.3 MV Underground network behaviour

4.3.3.1 Cable behaviour

The first analysis consisted in determining the **cable failure causes**, in which all external causes were eliminated, as the focus of this work is to determine cable component failure behaviour. External behaviour cannot be controlled or predicted and also alters the perception of the actual component's behaviour. For this reason incidents with the following causes were not considered in this study: predicted incidents (network works and client agreement), compelling reasons (network, external entities or networks and weather), other networks and human (see Section 2.3.5). The MV cable failure causes are represented in proportion in the figure below (Figure 4.10). So 68% of the incidents in cables are due to the equipment itself, mainly because of insulation faults (84%) and material ageing (15%), which can be a result of deterioration and ageing factors mentioned in Section 3.2.2.

After analysing the main cable failure causes, it was important to access the **impact** of **cable failure** on the overall MV **underground network**. For this analysis the components that caused incidents were arranged into three groups: cables, cable accessories and others (which include "*undamaged*", transformers, circuit breakers, etc). Analysing Figure 4.11 it is possible to conclude that cable and cable accessories account for the majority of the underground failures, the cables themselves account for more than 50% of the incidents, thus the importance of this work. The average cable incident duration is 161 minutes. When the duration of an incident is longer than 4h (240 min), according to the **GIRDN** there should be a technical explanation for it and also an inquiry/report must be written.

The next step was to analyse the **incident distribution** along the MV underground network and identify regions with higher incident/failure rates. For this analysis only networks with more than 100km in length are considered. These regions are more important to analyse as they will have a higher impact because they are, mostly, in highly populated areas – cities or urban areas (which means a lot of affected customers). After some analysis, there was another reason for not considering the regions with less than 100km, is that areas/regions with few cables and incidents will result in abnormally high failure rates, because of these traits. This will inflate the results, leading to misleading and/or wrong conclusions.

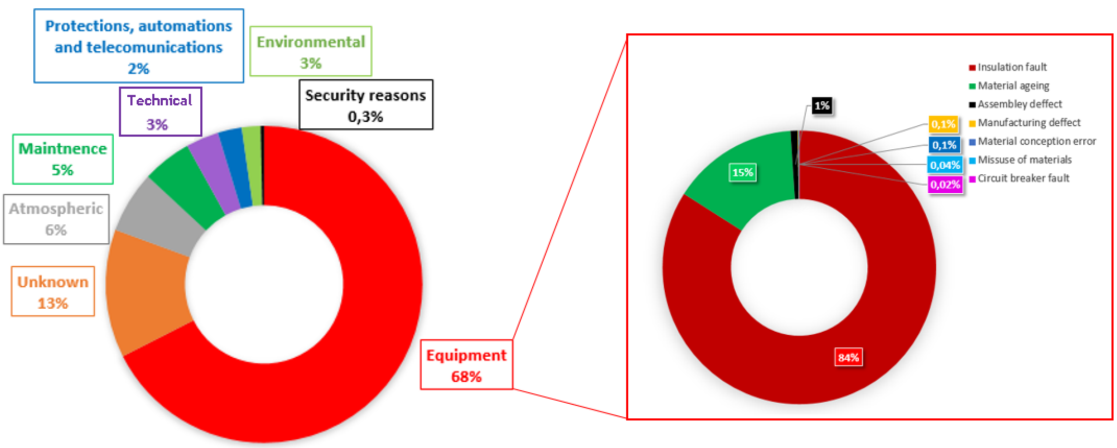


Figure 4.10: Undeground cable failure causes

The failure rates were determined according to formula 3.1, with the difference that the failure rate was per 100km. The reason for having the failure rate per 100km is so the failure rate numbers are easier to relate to units, for example, 1 incident per 100km per year, instead of 0,01 incidents/km/year. The figure below shows (Figure 4.12) the regional distribution of failure rates versus the concentration of more than 100km of MV underground cables. There is **almost** an **exact** match between the areas with more cables and higher failure rates (marked with red circles). These regions belong to the DRCs: DRCP, DRCL and DRCS (see Figure 4.4) [7].

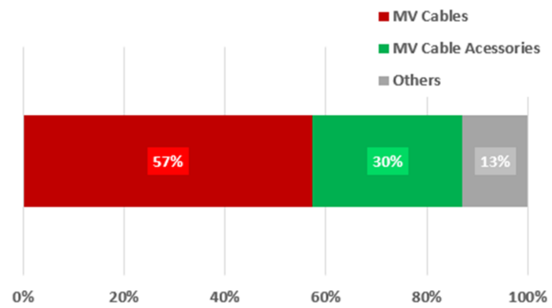


Figure 4.11: Components which cause underground network incidents

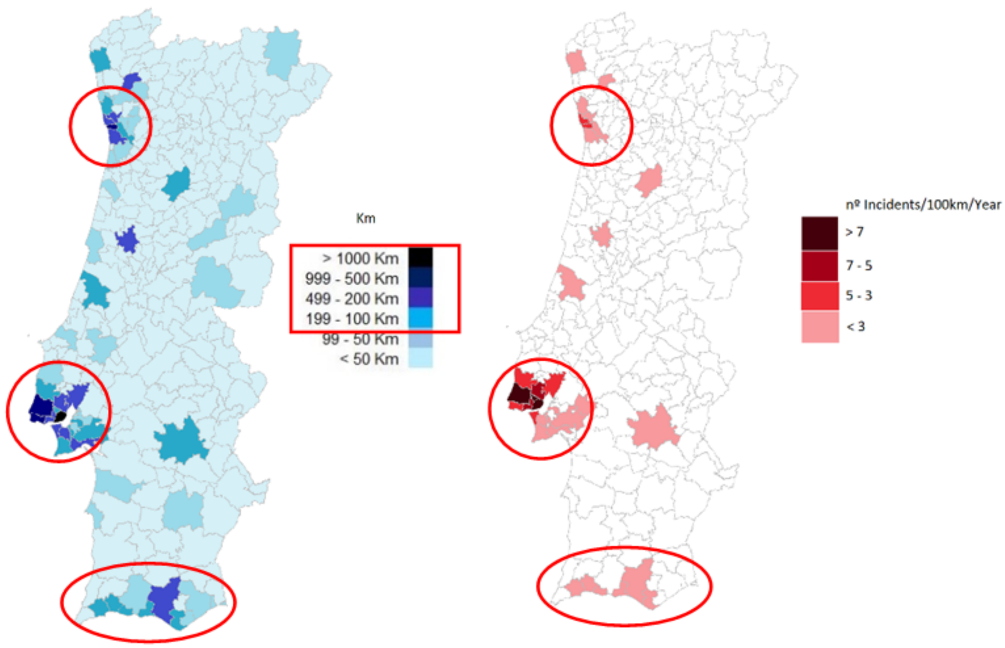


Figure 4.12: MV underground cable incidents distribution and cable concentration

The figure below shows the **failure rate per DRC** compared with the percentage of underground network, compared with the average failure rate (marked with a yellow line in Figure 4.13). The failure rate already represents the number of failures related to the network length, but having an idea of how much of the network is in each DRC (the blue columns) will help understand if a failure rate is in fact high or just an effect of having fewer cables. As expected the DRC$_E$ has the highest concentration of network (42% from the grand total) and also a high failure rate, which

[7] From now on coded

means it has lots of incidents despite having a lot of underground cable length. DRCA, DRCC and DRCD have high failure rates, but does not necessarily mean they have lots of incidents, as they have fewer cables, which is explained by these regions being more rural, thus predominantly overhead (as it is also cheaper). DRCB and DRCF are the second and third regions with more cables, with DRCB having above average failure rates. This analysis also helps to focus the study on regions with high network concentration and high failure rates, which is associated with highly populated areas, which is the case of DRCE, DRCB and DRCF.

In terms of cable failure rates **evolution over the years** (Figure 4.14), there have been periods of decreasing failures in the years 2006 and 2007, which can be explained by changes in the incidents registration procedure and database at *EDP Distribuição*. There also seems to be a general pattern of decreasing failure rates, followed by an increase. A possible explanations is that the decreasing years are a result of cable replacements and also the nonexistence of disturbing meteorological events. For example the years 2010, 2012 and 2013 were years were there were floods and storms like Xynthia (2010) and Gong (2013) (climate bulletins [8] [65]). The storms mean the possibility for lightning surges and floods, which can be some of the causes for cables failure increase, even though only 8% of cable failures are a result of atmospheric or environmental causes (See Figure 4.10).

Analysing the failure rates in relation to cable **voltage level** and cable type will help determine which ones have a poorer performance or if the high/low failure rate can be explained by the network length, as done previously for the regions.

The figures below represent the incidents per voltage level (Figures in 4.15). Figure 4.15b represents the failure rate compared with the cable length. So, as expected the 6kV network presents a very high failure rate, but it is elusive as it only contains 0,3% of MV cable length, which means that one or two incidents can be enough to generate a high failure rate. Also only 0,5% of the number of incidents happen at this voltage level (check Figure 4.15a). The 15kV network has a good performance, considering more that 50% of the MV cables are 15kV, despite being responsible for 37% of all incidents. On the other hand, the 10kV network represents 30% of network but has more than 50% of the incidents over the years, which results in a high failure rate. The 30kV network does not have a worrying performance, with only 6% of all incidents and 12% of the network.

[8] IPMA Climate bulletins - Contain information on climate behaviour, including storms.

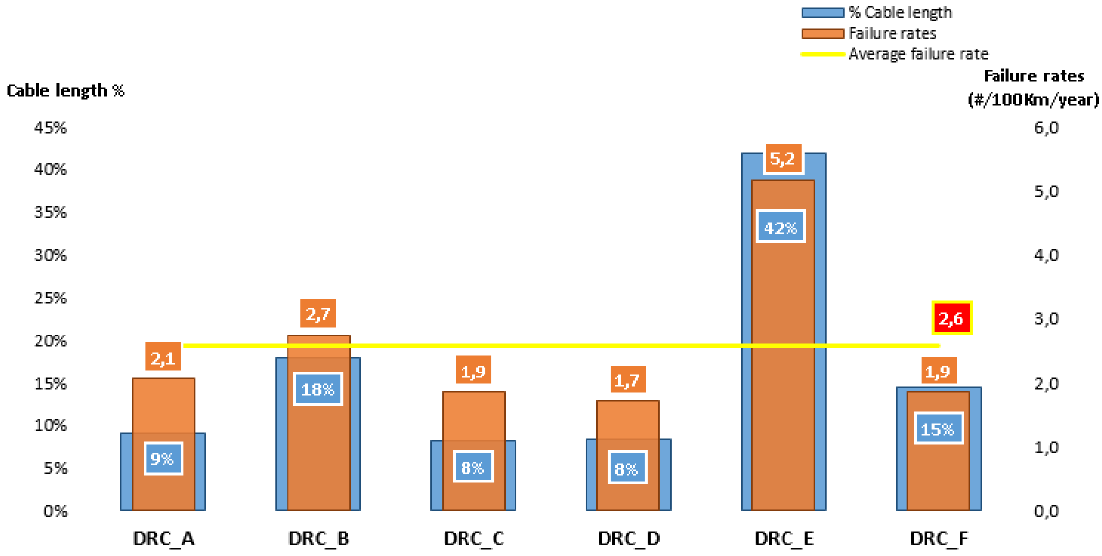


Figure 4.13: DRC failure rate versus network length percentage

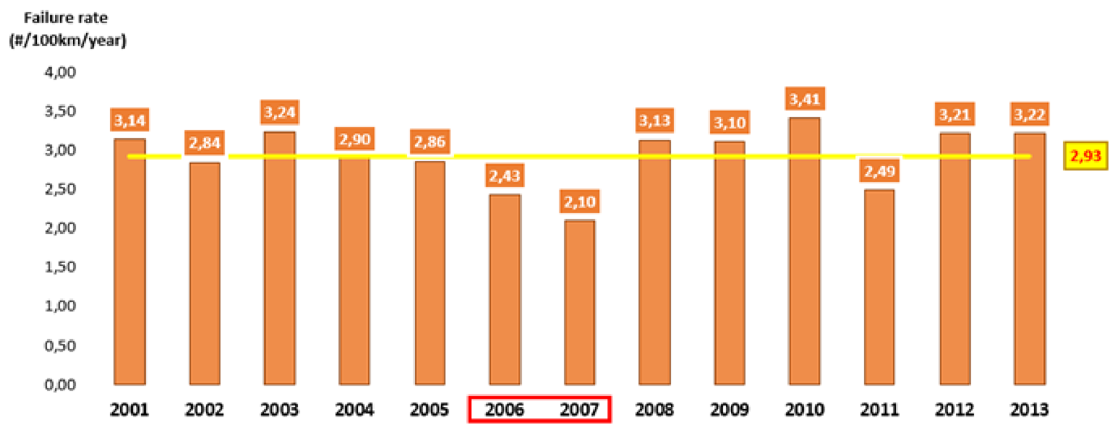
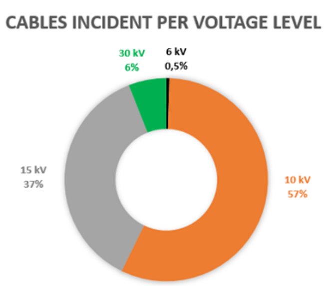
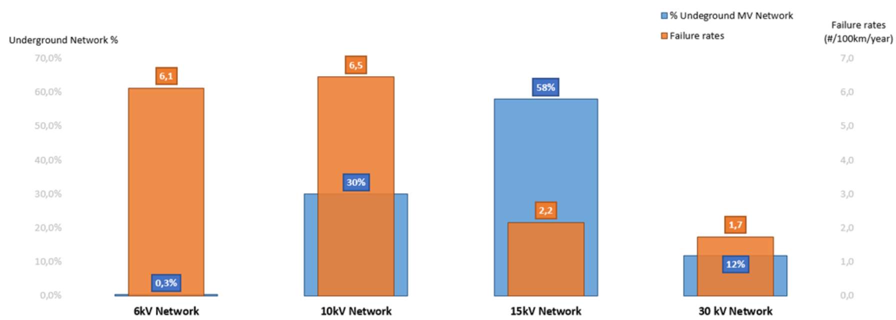


Figure 4.14: Year faiure rate evolution



(a) General network voltage level distribution



(b) Voltage level failure rate versus network length percentage

Figure 4.15: MV Network voltage level failures

The next step was to analyse cable type behaviour to see whether any of the **cable types** are more prone to fail. The figure below (Figure 4.16) summarizes the oil and dry cables failure rates versus the percentage of cables of each type. Oil cables have a worse performance than dry cables, with a high failure rate (almost 5 incidents/100km/year), on the other hand they also are only accountable for 15% of the network. But in this case it is 15% of the whole MV underground network means several hundred km of cables. Comparatively, dry cables have a lower failure rate (about 3 incidents/100km/year), but for about 15% of the whole MV underground network. So oil filled cables have a worse performance, as other utilities have experienced (see Section 3.3) and for this reason are slowly being replace with the dry cables, which have a better performance.

This study of cable incidents, besides determining MV underground cable network characteristics, helped to determine important areas to analyse in further detail regarding the impact of other variables on cable failure (eg. Temperature, load, soil type). The regions with the highest failure rates (as identified in Figure 4.12) will be the focus for the accessory and seasonal behaviour, but also for the statistical analysis performed in Section 4.4. These regions also have a high percentage of cable caused incidents in their underground network (approximately 50%). The regions of focus are: Porto, Lisboa and Faro.

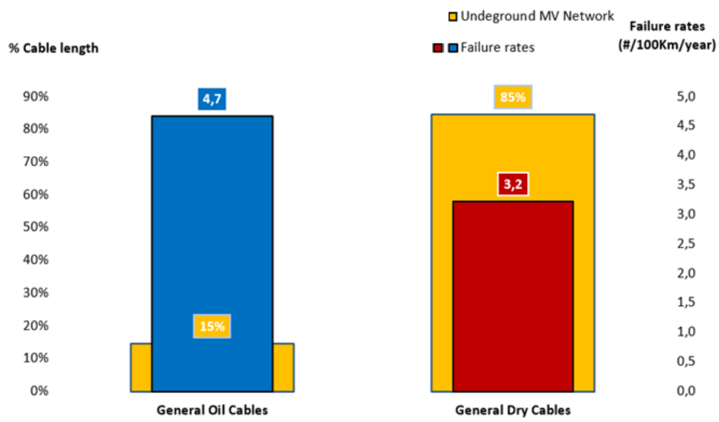


Figure 4.16: Cable type failure rate versus network length percentage

4.3.3.2 Cable accessory behaviour

This section will present a brief analysis of cable accessories, as it is **not** the focus of this work, despite accessories being related to cable failure (see Section 3.3) and are accountable for 30% of the number of incidents in the MV underground network. There are three kind of cable accessories: termination (**T**), derivation (**D**) and junctions (**J**). The percentages (number) of accessories of each kind which exist in the MV underground network are summarized in the table below (Table 4.3). This table also describes the percentage of accessory incidents and probability related to each type. Analysing this table it can be concluded the **D** accessories represent more than half of the accessory type, despite this, their failure probability is low. **T** accessories have the highest failure probability, despite only account for 12% of the number of accessories. This can be explained by the fact that lots of terminations are actually transitions from underground to overhead, or vice-versa, which results in a higher vulnerability than the remaining types, as they are more susceptible to exterior interaction.

Table 4.3: Summary of MV underground cable accessories type and incidents

Acessory type	Network (%)	Total acessory incidents (%)	Failure probability (%)
T	12%	51%	8%
D	55%	0,3%	0,01%
J	33%	49%	3%

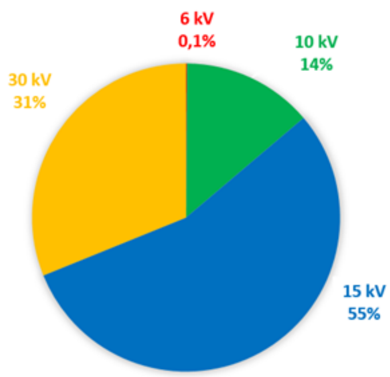


Figure 4.17: Cable accessory voltage distribution

The tables and figure below represent the analysis per voltage level distribution in number an failure probability for MV underground accessories (Tables 4.4 and 4.5, Figure 4.17).

Table 4.4: Cable accessory various voltage level percentages

Accessory type	6kV Network	10kV Network	15kV Network	30kV Network
T	0,1%	9%	64%	27%
D	0,04%	11%	57%	32%
J	0,2%	19%	49%	32%

As expected and observed for cables (see Figure 4.9a) the 15kV is the predominant voltage level in any of the accessory types and for the overall accessories. Regarding the failures, in a similar way to the cables the 6kV presents a high failure probability, which is explained by the few number of components with this voltage level (not even 1%), which results in a misleading probability. As expected and for reasons explained above, the Terminations have the overall highest failure rates.

In terms of incident distribution the accessory have the same failure concentration as cables, in the regions identified in section 4.3.3.1, as they are also areas with more accessories (and more cables).

Table 4.5: Cable accessory failure probability per voltage level

Acessory Type	**Failure Probability (%)**			
	6kV Network	10kV Network	15kV Network	30kV Network
T	44%	24%	6%	8%
D	—	0,1%	0,004%	—
J	10%	7%	3%	0,4%

The predominant age is lower or equal to 10 years and the accessory type with the oldest components are the Derivations.

A future more in depth analysis can be made, accessing accessory failure seasonality, material type (heat versus cold retractable), installing process, failure causes and inclusion into a cable failure prediction model.

4.3.4 Cable incidents' impact on the underground network QoS

This section determines the **impact** of **cable** failure on the underground network **QoS**. As explained in Chapter 2 (See Section 2.3.3), QoS of service can be quantified through indicators, which for this section means calculating the impact for the following indicators: MAIFI, SAIDI and SAIFI. The reason for only calculating these indicators has to do with the available information for the analysis.

The first step was to analyse the types of duration associated with cable, cable accessories and other network components incidents (Figure 4.18). Associate to cable incidents are mostly associated LD, which represent 45% of the total number of these kinds of incidents. As for SD neither cables nor cable accessories have a big impact, so these incidents are mostly associated to other components. The explanation is that other components include protection units which act in a very short period of time (less that 1 minute).

The figures below represent the cable impact on the three QoS indicators (Figures 4.19, 4.20 and 4.21) and as expected have a big impact on SAIFI and SAIDI as they are calculated based on LD incidents, which cables are responsible for the majority. Also, it is possible to see an improvement in the indicators over the years (despite SAIFI appearing slightly variable), as it has been gradually decreasing in the MV underground network, which proves the network operator's concern with improving QoS (see Chapter 2). Also, as expected, there is a very low impact of cable failure on MAIFI.

An important conclusion from this study is that reducing cable failures will have a **significant impact** on the MV distribution network's overall underground network QoS performance. This reduction can either be done resorting to failure prediction models, which lead to preventative failure measures such as replacement or refurbishment. Further suggestions for QoS will be made in Section 4.5.

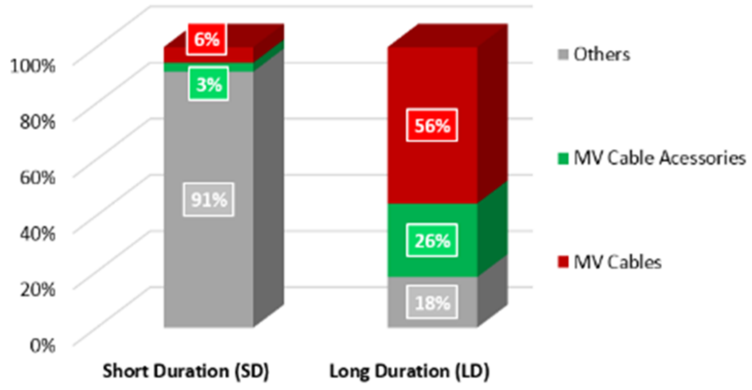


Figure 4.18: MV underground network incident duration types and components responsible for the incidents

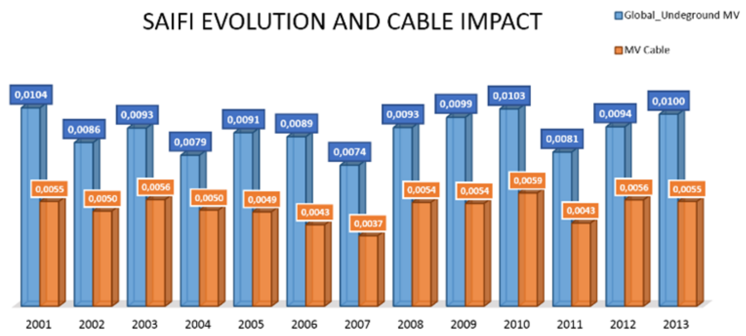


Figure 4.19: Cable failure impact on SAIFI QoS indicator over the years

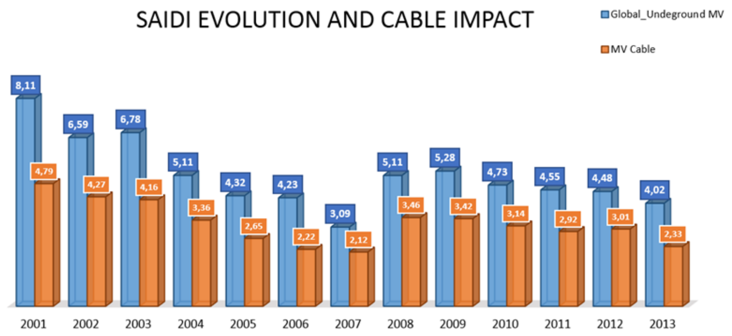


Figure 4.20: Cable failure impact on SAIDI QoS indicator over the years

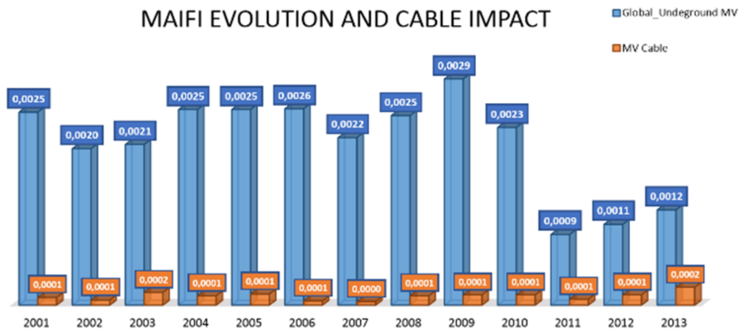


Figure 4.21: Cable failure impact on MAIFI QoS indicator over the years

4.3.5 Cable failure seasonal behaviour

This section analyses the **possibility** of seasonal cable failure behaviour and associate it with several possible variables such as: temperature and load. The focus of this analysis will be the three identified regions in Section 4.3.3.1: Porto, Lisboa and Faro. For a first analysis is a general observation of failure behaviour in the various months, as shown in Figure 4.22. There seems to be some relation between temperatures and incidents, not linear for the overall year, but in some seasons there seems to be a linear relationship.

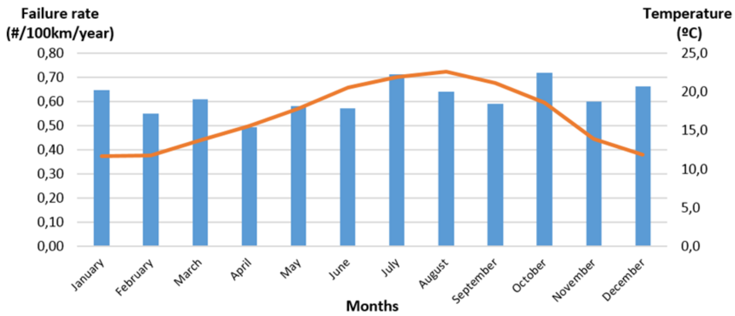


Figure 4.22: General Temperature and failure seasonal variations graph

The seasonal behaviour can become more apparent in a more specific region analysis, as the temperature is more accurate. The temperatures used are predictions and not actual measurements, as this information was not available (explained in Section 4.2.2). The three figures displayed below (Figures 4.23, 4.24 and 4.25) represent the seasonal variation of the total number of incidents over the study period and the average temperature per month based on the predictions for each region. Also a linear correlation coefficient was determined, using Excel's "Correl" function (**Pearson's linear correlation**) for some parts of the year that seemed to be correlated. This parts are marked in the figures in red and yellow rectangles and correlation results are in the rectangles on the left of the graph.

Months	CORREL
Jan - Ap	-0,99
Ap - Jul	0,68

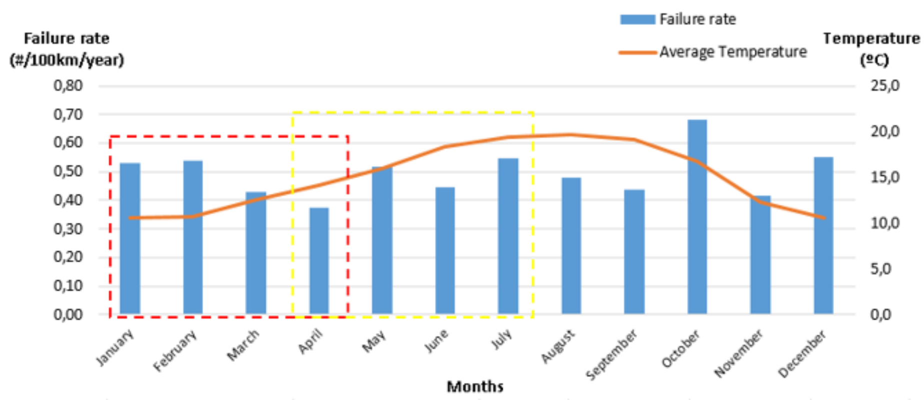


Figure 4.23: Temperature and failure rate correlation coeffecients and graph for Porto Region

There seems to be a correlation between failure rates and spring/summer months, as temperatures increase over this period. Another interesting study would be to determine if days with high temperature amplitude mean more incidents, as this is a cable deterioration factor (explained in Section 3.2.2). But there was no available data for this study (suggestion for future work). Another suggestion would be to determine if this amplitude and cable failure correlation based on the region's predominant soil type, as seen in Section 3.2.3, there are soils that are better than others at heat dispersion. So there can be certain regions with more tendency for cable hot spots because of poor heat dispersing soil.

In section 4.4 statistical tests will be performed to determine if there is statistical evidence for this correlation (failures and temperature), as for this section the correlation was determined based on the total number of incidents and an average temperature per month, which can be misleading.

Months	CORREL
Jan - Ap	-0,75
Ap - Jul	0,87

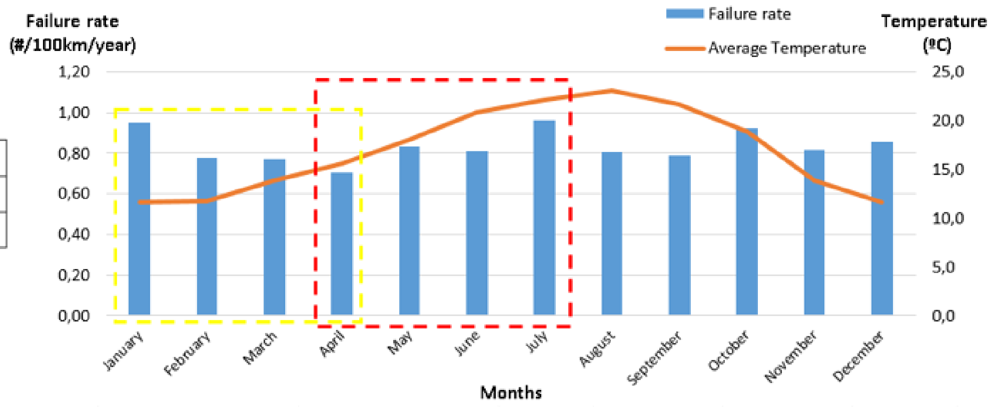


Figure 4.24: Temperature and failure rate correlation coefficients and graph for Lisboa Region

Months	CORREL
May - Nov	0,81
Ap - Nov	0,76
Ap - Aug	0,97
Jan - Mar	0,85
Jan - Aug	0,81

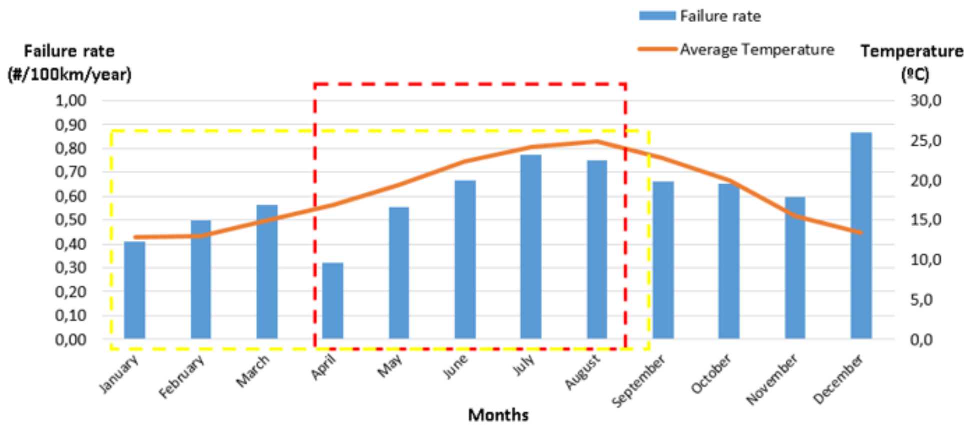


Figure 4.25: Temperature and failure rate correlation coefficients and graph for Faro Region

Daily load variation is also a possible variable to correlate with incidents, as they also have a seasonal behaviour. There will be certain periods of the year that the behaviour is different (e.g. summer - tourist areas increase load and other regions a decrease as it is the holiday season) and others where it is similar (e.g. winter there is a general increase, related to heating and also working period). The three figures below are the average load and incidents (failure rate) per month variation for the three studied regions (Figures 4.26, 4.27 and 4.28).

There seem to be a difference between the regions variable impact, for example, Lisboa region seems to be more affected by load variation, which is explained by the very high network concentration and also that the demand is much higher, meaning that cables are probably operated at a higher level than they were design to. For Faro region, there seems to be a high correlation between both temperature and load variations and incidents. Finally, in Porto it seems that temperature has some impact, but the regions' climate is moderate and the loads are not too high, so another possible explanation could be cable deterioration or ageing, but there is no information to pursue this hypothesis. Some of the correlation coefficients calculated are strong and are marked in red (between [0,8 ; 1]). When calculating linear correlations it does not assess causality, because that is not what correlation is. So in order to determine if there is any significance for the observed behaviour a statistical test must be done, which will be further discussed in the statistical analysis Section 4.4.

Months	CORREL
Jan - Ap	0,97
Ap - Jul	0,24
Aug - Oct	0,42

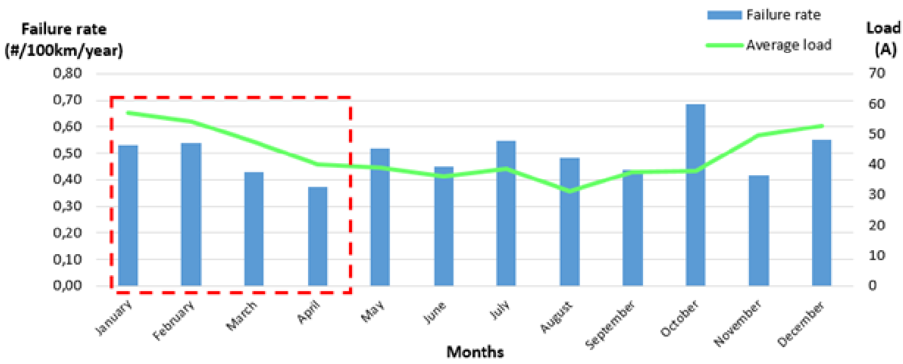


Figure 4.26: Load and failure rate correlation coefficients and graph for Porto Region

Months	CORREL
Jan - Aug	0,51
Jan - Ap	0,76
Ap - Aug	0,77
Oct - Dec	-0,85

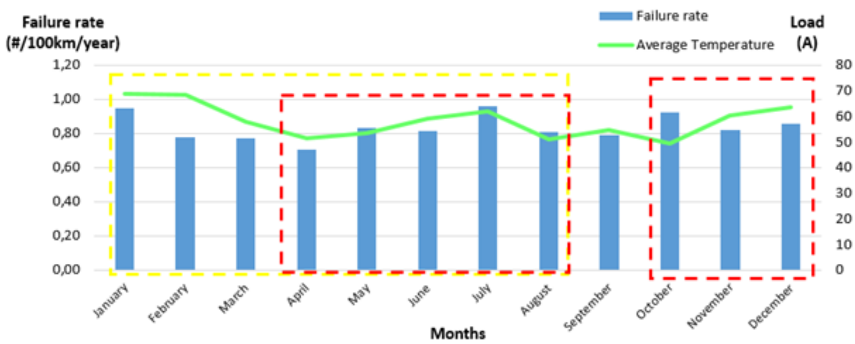


Figure 4.27: Load and failure rate correlation coefficients and graph for Lisboa Region

Months	CORREL
Jan - Mar	-0,54
Ap - Sep	0,87
Ap - Jul	0,88
Aug - Nov	0,92

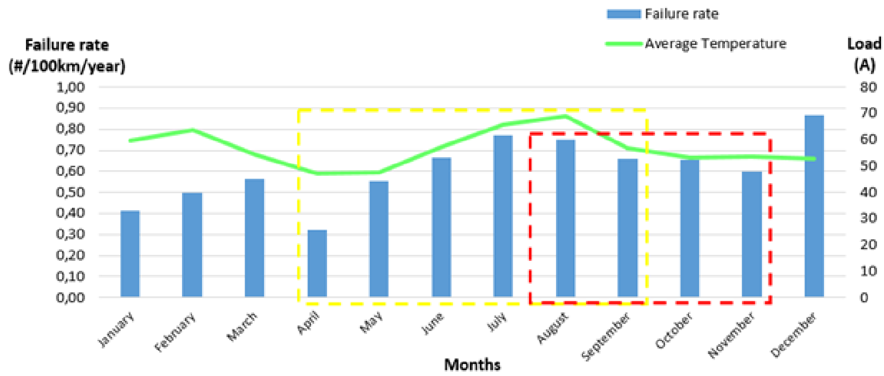


Figure 4.28: Load and failure rate correlation coefficients and graph for Faro Region

The possibility of combining soil type with load and temperature variation could probability give an indication of network spots with a higher failure probability, because possibly a good heat conducting soil can both disperse the cable heat but also mean the cable will heat up because of the rise in ambient temperature. But the fact that the soil is a good heat conductor also can mean big temperature amplitudes during the day, whereas a worst conductor can have a more slow variation, but also means that when the cable heats up from use it will be harder to disperse heat. This should be looked into with more detail, for future work.

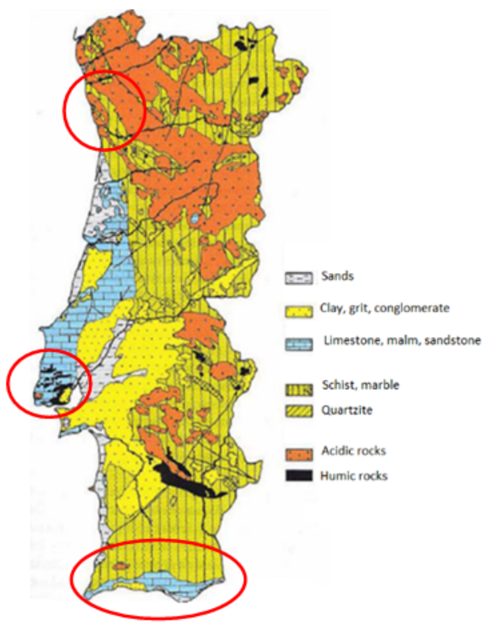


Figure 4.29: Soil type in continental Portugal with chapter studies regions identified

4.4 Statistical analysis

4.4.1 Statistical analysis methodology

For the statistical data analysis there were three phases (Figure 4.30) and it was developed using the statistical software **R** and **MATLAB**. The analysis was done for the three regions identified in Section 4.3. For the **first** part a statistical summary was made, to understand the spread of the data (incidents, temperature and loads). The **second** part conducted a detailed dependence and correlation analysis of cable incidents with temperature and load variation, which was validated comparing the results with scatter plots and also, for the dependence test, hypothesis testing. The **third** and last part consisted in fitting probability distributions to the number of daily cable incidents over the year, to determine the number of probable daily failures. For this part, days without incidents were not considered. Various distributions were fitted to the data and the best fist was determined (including parameter estimation).

For each phase data was organized according to the analysis and the existing data for temperature and loads.

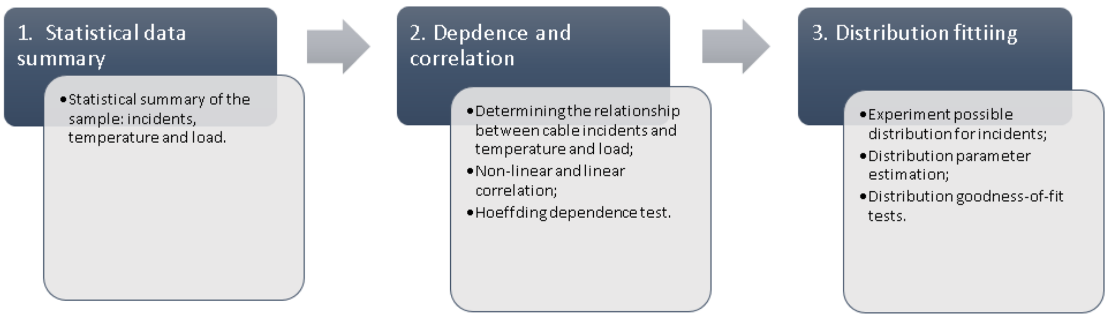


Figure 4.30: Statistical analysis methodology

4.4.2 Statistical data summary

This section will present a statistical data summary for the incident, temperature and load databases, which will give an idea of how the data is organized.

The statistical data summary is also known as the five/four number summary (five if it includes the mean) and is usually plotted into the called box-plots. The data used for this four data plot summary, besides the box plot 4.31 only include information from the three identified regions (see Section 4.3.5).

The four number summary for each region is represented in the figures below (Figure 4.32 to 4.35).

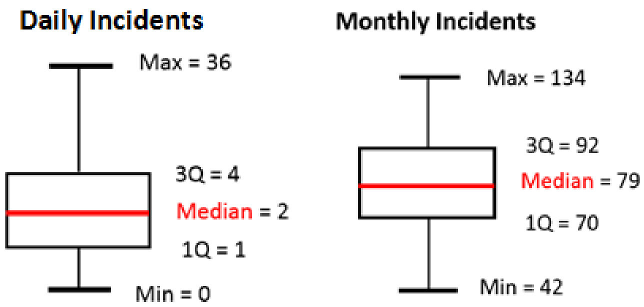


Figure 4.31: General data box plot summary

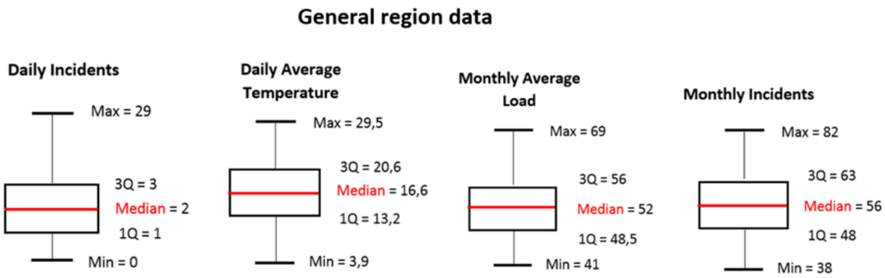


Figure 4.32: General 3 region data box plot summary

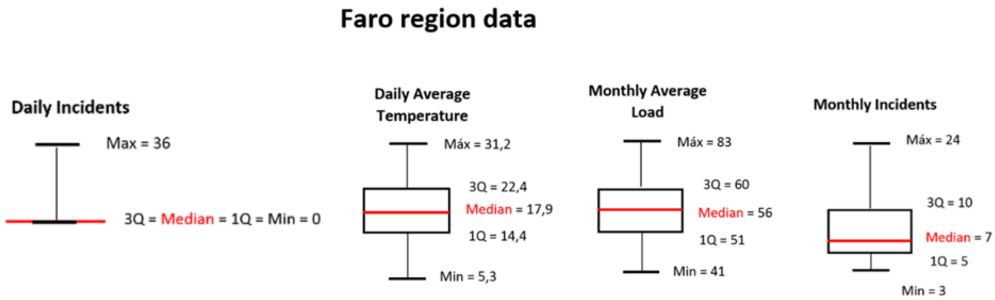


Figure 4.33: Faro region data box plot summary

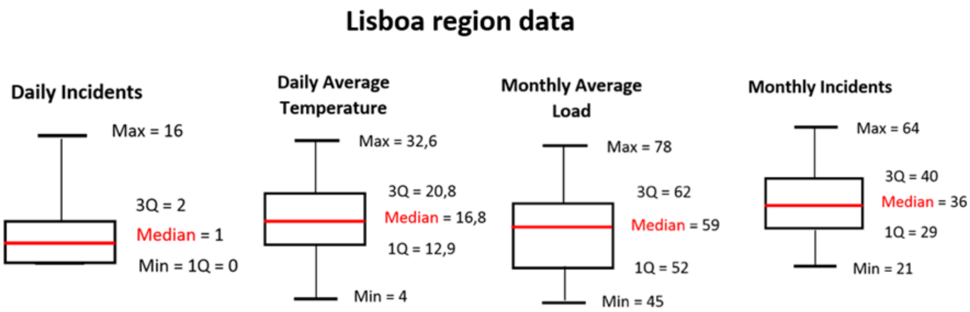


Figure 4.34: Lisboa region data box plot summary

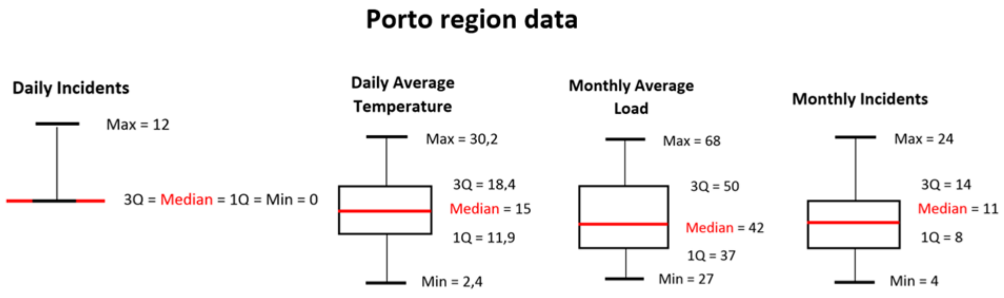


Figure 4.35: region data box plot summary

The **boxplots** are a good way of seeing how data is distributed, whether it is evenly distributed (e.g. like the temperature and monthly incidents) or whether it is concentrated near maximum or minimum values (e.g. like the daily incidents). The median is the value that separates the higher half of the data sample from the lower half. It is not the same as the arithmetic average, even though there is some crossover in the definition, as average is also referred to a central or typical value, meaning that the median and average can coincide. In the case of the data presented the average was approximately the same as the median, but was not included in the boxplot, as it is not a value typically included. A typical boxplot has the aspect and meaning are represented in the figure below, as it helps to understand the data's box plots (4.36).

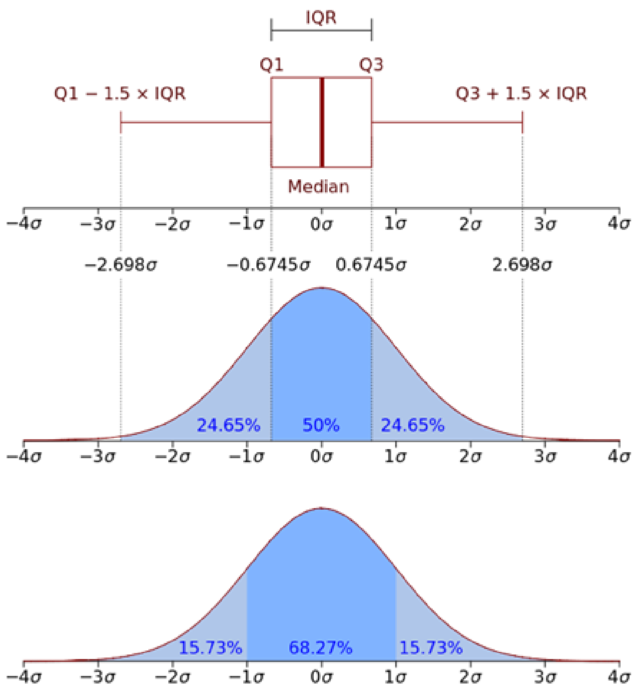


Figure 4.36: Boxplot meaning [16]

4.4.3 Dependence and correlation

This section will present the correlation and dependence between cable incidents and temperature/load. The dependence test used was **Hoeffding's test** and for **correlation**, **Kendall's** non-linear correlation coefficients and **Pearson's** linear correlation coefficient. The data analysed refers only to underground cable failures, ambient predicted temperature and MV underground network average monthly load.

The correlation and dependence test were computed using existing functions in the used software for each of the tests.

The Hoeffding dependence test is a rank based approach, which computes a value for the measure of dependence "D" . The correlation tests were divided into non-linear and linear, for determining Kendall's and Spearman's coefficients, respectively. The correlation coefficients measure the association between two measured quantities that can be linear or non-linear. The coefficients vary between -1 and 1, being these the maximum values for a positive association (positive coefficient) or a negative association (negative coefficient). A positive associations means both quantities vary in the same direction, either increasing or decreasing, while a negative association means both quantities vary in opposite directions, one increases and the other decreases or vice versa. These coefficients measure the degree of correlation. The difference between correlation and dependence is that dependence implies correlation, but not the other way round.

The analysis process consisted in analysing data scenarios based on the available data and also based on some behaviour observed in Section 4.3.5. The scenarios basically consisted in detailing the daily values to monthly and regional values. The results for both load and temperature correlation/dependence analysis with cable failure are summarized in Tables 4.6 and 4.7, respectively.

Analysing the results of the tests there is a very low, nearly non-existent, dependence for the temperature or load and cable failures. For a strong dependence Hoeffding's D should be somewhere near 1. Also most of the correlations are low, for a large number of datasets. There is a higher correlation for a lower dataset, concentrated by month, which is not a strong indicator for correlation evidence. For a good correlation the coefficients should be larger than 0,8 , which is not the case for any of the determined correlations.

Based on the general results there does **not** seem to be **enough statistical evidence** for a relation between cable incidents and load/temperature variation, particularly for the daily analysis. In more concentrated analysis, with a smaller data set, there seemed to be a higher relationship, but still not strong enough. Maybe with more detailed data or more data points, a stronger relationship could be found.

Table 4.6: Temperature and cable incidents correlation and dependence results

Scenario description	Kendall coefficient	Pearson coefficient	Hoeffding D	Nº of points (dataset size)
- All year - Daily values - All 3 regions	0,0568	0,0645	0	2071
- All year - Daily values - Faro	0,0189	-0,0249	0	479
- All year - Monthly values - All 3 regions	0,1675	0,1083	0,02	76
- Hot months - Daily values - All 3 regions	0,1258	0,214	0,01	663
- Hot months - Monthly values - All 3 regions	0,5375	0,6444	0,19	24
- Hot months - Cumulative - All 3 regions	0,6670	0,8703	—	4
- Incident per temperature - All 3 regions	0,0892	0,0915	0,1	26

Table 4.7: Load and cable incidents correlation and dependence results

Scenario description	Kendall coefficient	Pearson coefficient	Hoeffding D	Nº of points (dataset size)
- All year - All months - All 3 regions	-0,1640	-0,1691	0	48
- Faro - Months: Ap - Nov	0,1008	-0,0039	-0,01	32
- Faro - Months: Ap - Sep	0,0840	-0,0032	-0,02	24
- Lisboa - Months: Jan - Sep	-0,0685	0,0072	-0,01	36
- Lisboa - Months: Ap - Aug	0,0618	0,1343	0	20
- Porto - Months: Jan - Ap	-0,2501	-0,4103	0,01	16
- Porto - Months: Sep - Dec	-0,0350	-0,0597	-0,02	16

4.4.4 Distribution fitting and Goodness-of-fit tests

As the results in the previous section show there is not sufficient evidence for a strong relation between incidents and temperature and/or load, which would be an indication for joint probability distribution fitting. Instead, this section will address the daily cable failures, excluding days without any failures. The aim is to determine a daily cable probability distribution function. In order to accomplish this, the distribution types needed to be chosen, followed by a goodness-of-fit test in order to determine which distribution better fits the empirical data.

Distribution fitting, as mentioned above consists in fitting various probability distributions to the empirical data. Typical distributions for life-time analysis were used (see decision tree in Annex A.2), which were: **Lognormal**, **Weibull**, **Gamma** and **Exponential**. These distributions were fitted to the data and the figures below represent the comparison for **CDF** and the **PDF** between the empirical and fitted distributions (Figure 4.38).

The Figure on the right (4.38 a) represents the PDF and EPDF, while Figure 4.38 b) represents the ECDF and CDF, where the empirical (E) is the data and the remaining are the fitted distribution. The procedure for obtaining these graphs started with the data histogram (Figure 4.37), which was transformed into a PDF for empirical data (see Fig 4.38 a) that is a representation of the various number of incidents probability, based on the frequencies and total number of occurrences. The distributions, based on their PDF functions, are fitted to the EPDF. Afterwards, the CDF or just distribution function is built, which describes the probability that a real random value "X" with a given probability distribution will be found at a value less or equal to "x", where "x" is the incident number in a day. For example, the probability of in a day occurring 10 or less incidents is approximately 95% (see Figure 4.38 b), because this is the accumulative probability of all the incident numbers until 10. There is some error in these probabilities, as the model does not include days when there are no incidents.

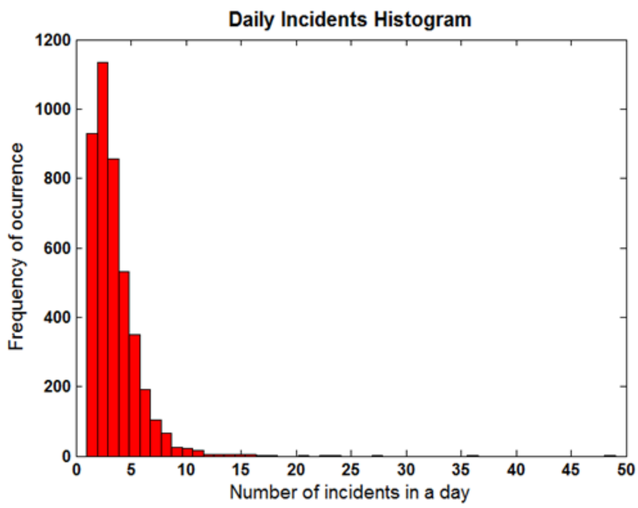


Figure 4.37: Number of daily incidents histogram

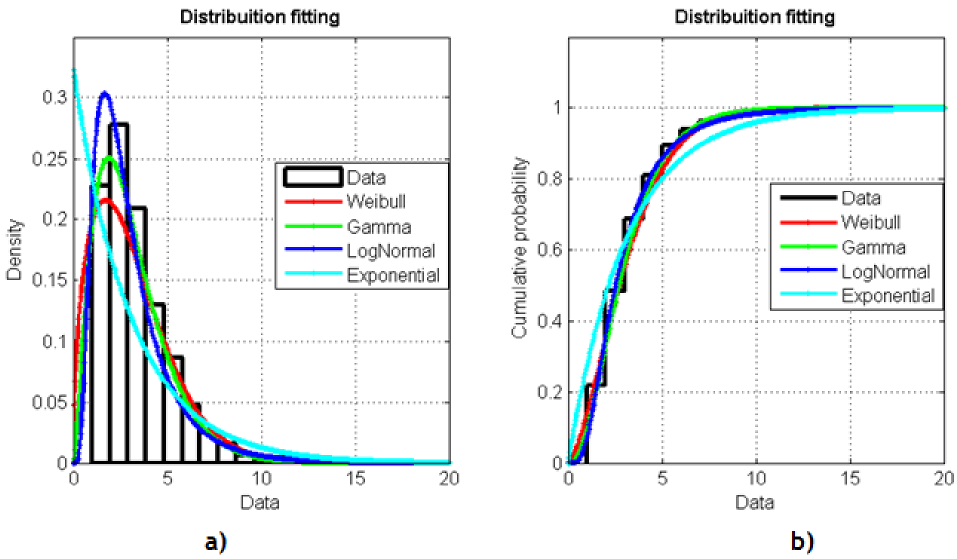


Figure 4.38: Fitted distributions: PDF and CDF

The process of distribution fitting included estimating the distribution's parameters with a 95% **confidence interval** (**CI**). The process for approximating the distributions and estimating their parameters was done using the software's *fitdisp* function, which is a built in function. In this case, this function used the **Maximum Likelihood Estimation** (**MLE**) method for the parameter estimation. This method is commonly used in parameter estimation for distribution fitting. Each distribution function has its parameters and formulas. The formulas and parameters for each fitted distribution are [66]:

- **Weibull distribution:**
  PDF fucntion:

$$f(x|a,b) = \frac{a}{b} \times \left(\frac{x}{a}\right)^{b-1} \times e^{-\left(\frac{x}{a}\right)^{b}} \tag{4.1}$$

  CDF function:

$$F(x \mid a,b) = \int_{0}^{x} ba^{-b}t^{b-1}e^{-\left(\frac{x}{a}\right)^{a}} = 1 - e^{-\left(\frac{t}{a}\right)^{a}} dt \tag{4.2}$$

  Where:
  a - scale parameter

  b - shape parameter

- **Gamma distribution:** PDF fucntion:

$$f(x|a,b)\frac{1}{b^{a} \times \Gamma(a)} \times x^{(a-1)} \times e^{\frac{-x}{b}} \tag{4.3}$$

CDF fucntion:

$$F(x \mid a,b) = \frac{1}{b^a \Gamma(a)} \int_0^x x^{a-1} e^{\frac{-x}{b}} dt \tag{4.4}$$

Where:

a - rate parameter

b - shape parameter

- **Lognormal distribution:** PDF fucntion:

$$f(x|\mu,\sigma) = \frac{1}{x \times \sigma \times \sqrt{2\pi}} \times e^{\frac{-(ln(x)-\mu)^2}{2\times\sigma^2}} ; x > 0 \tag{4.5}$$

CDF function:

$$F(x \mid \mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^x \frac{e^{\frac{-(\ln(t)-\mu)^2}{2\sigma^2}}}{t} dt \tag{4.6}$$

Where:

$\mu -$ mean parameter

$\sigma - standarddeviationparameter$

- **Exponential distribution:** PDF fucntion:

$$f(x|\mu) = \frac{1}{\mu} \times e^{\frac{-x}{\mu}} \tag{4.7}$$

CDF function:

$$F(x \mid \mu) = \int_0^x \frac{1}{\mu} e^{\frac{-t}{\mu}} dt = 1 - e^{\frac{-x}{\mu}} \tag{4.8}$$

Where:

$\mu - meanparameter$

- Where x in all the functions is the data.

The results for the distribution parameters and the confidence bounds are summarized in the table below (Table 4.8). So it can be concluded that with a 95% CI that each parameter contains the true value.

The second step consisted in determining which distribution is the data's best fit, which was determined using the **Kolmogorov-Smirnov test**. This test gives a p-value which will help to decided which distributions can be rejected, as it determines the **goodness-of-fit** using **hypothesis testing**. **The hypothesis** are:

Table 4.8: Fitted distribution results: parameters and confidence bounds

Distribution function	**Estimated parameters**	**Confidence bounds (CI=95%)**
Weibull	a =3,46901 b =1,52607	a $\in [3,39738;3,54215]$ b $\in [1,49507;1,55771]$
Gamma	a =2,581, b =1,20086	a $\in [2,47967;2,68647]$ b $\in [1,14893;1,25513]$
Lognormal	$\mu = 0,925155$ $\sigma = 0,636619$	$\mu \in [0,906022;0,944289]$ $\sigma \in [0,623376;0,650442]$
Exponential	$\mu = 3,09941$	$\mu \in [3,00835;3,19469]$

Ho: *"The fitted distribution is a good fit for the empirical data"*

H1: *"The distribution is not a good fit for the empirical data"*

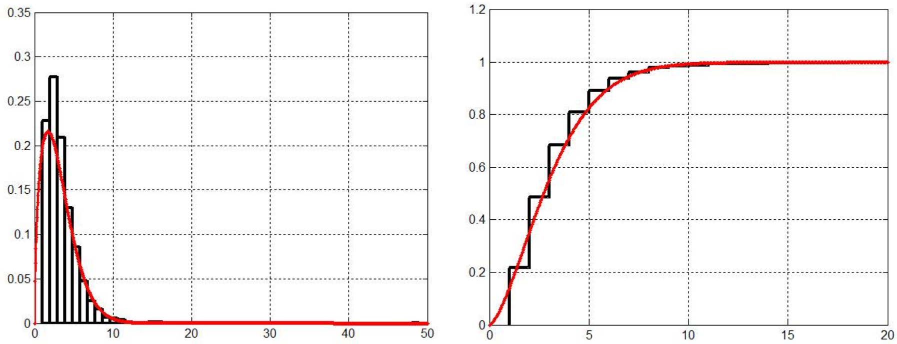
In this case the null hypothesis (**Ho**) is that the distribution is a fit for the data. So, the **p-value** will say if the Ho can be rejected, meaning that the distribution is not a fit. For this work, the **threshold p-value** for rejecting the null hypothesis was 5% (normally used value). The table below summarizes the result of the test (Table 4.9).

Table 4.9: Kolmogorov-Smirnov goodness-of-fit test results for the fitted distributions

Distribution function	**KS test p-value**	**Null hypothesis**
Weibull	0,9891	Cannot be rejected
Gamma	0,6636	Cannot be rejected
Lognormal	0,0367	Rejected
Exponential	0,2702	Cannot be rejected

Analysing the table above, based on the p-value, only the Lognormal distribution can be rejected as a distribution fit for the data. For the remaining distribution function the high p-values mean there is not sufficient statistical evidence to reject them as a fit for the data. Although, the Weibull distribution has the highest p-value, at approximately 99%. The p-value tell how likely the observed data would be is the null hypothesis were true or, in order words, the strength against the null hypothesis (the smaller the higher the strength against it). So, given the results presented it can be said that the Weibull distribution function is the best fit. This function is usually used for fitting lifetime data, which is the case for MV underground cable failures.

Determining a probability distribution means assigning the probability to each measured asset, in this case the probability of having none, 1, 2 or more cable incidents in a day, in the MV underground distribution network. The distribution parameters were estimated with a 95% CI. The two figures below show the fitted Weibull to the the data (Figures 4.39a and 4.39b).



(a) PDF - Fitted Weibull function to the empirical data

(b) CDF - Fitted Weibull function to the empirical data

Figure 4.39: Pictures of animals

This distribution fit will give a conditional probability, which is knowing that there is going to be a cable incidents, what is the probability that there will be 1, 2 ,3 or other number of incidents. These probabilities are determined based on the CDF.

A suggestion for future work is determining the distribution that fits a daily number of incidents, including the hypothesis of having zero failures, comparing the fitted distributions with the current results and building a prediction model, which can be updated for every year's incidents. It would be interesting to conduct a survival data, but for that analysis the cable ages of fail assets needed to be known or the failed cable lengths.

4.5 Improvements and future developments

This section will describe suggestions for improvements and future work, based on the experience of developing this thesis and the main obstacles faced. These suggestions can be grouped into three areas:

- Databases and information;
- Studies;
- Models.

Missing or inaccurate data and/or incompatible information was an obstacle to overcome. So the first suggestion is to improve information registration by a more sophisticated report table, in which instead of manually entering the data, the report is filled out selecting options which limit the choices as it is being completed. Also it would be interesting in the future to connect incident databases with other information like loads, temperature and network characteristics.

For cable failure and temperature, it would be interesting to determine if temperature amplitude can be correlated with cable failure. Maybe regions with a high temperature amplitude can have more incidents. A suggestion would be to determine one to three days before the failure data an average or maximum temperature amplitude to which the cable, or the region where the cable is buried, were subjected to and determine if there is any relation between them. Also, it would be interesting to do associate soil types were the temperature amplitude can be more severe, as temperature variation is in fact an ageing/deterioration factor.

It would be interesting to build a prediction model, based on statistical models, maybe using **Artificial Neural Network** (**ANN**), which determine the failure probability per region, taking into consideration temperature, load and time of year (day/month). Another interesting statistical study would be to determine the joint probability statistics of cable failures and temperature, maybe when there is more data evidence of the correlation between these variables. These models could even used for making AM decisions, when the failure probability is high a replacement strategy could be adopted.

This suggestions of future work and developments are hope that the work developed will be conitnued and used as an improvement of energy distribution quality.

It would also complete the understand of MV underground network if a more in depth study, including statistical study, on cable accessories. Specially comparing installation type and regional distribution of both failures and installation types.

Chapter 5

Conclusions and future work

This chapter states the conclusions of this thesis, listing and explaining the main findings and also suggestions for future work.

5.1 Conclusions and objective satisfaction

The main goal of this thesis was to determine and characterize the MV underground cable behaviour of the Portuguese distribution network. This study is innovative in the area as there was no previous in-depth study on the matter. The objectives included the characterization of the network and determining the networks main traits regarding cable failures, which included accessing the matter of cable seasonality.

The outcome of the analysis carried out in this thesis may be used for distribution operator asset management decisions and also improvements for the data acquisition process and the communication between databases.

This thesis provided the following contributions to knowledge:

1. **The importance of proper data acquisition for making reliable analysis.** As mentioned throughout this thesis, the quality of the existing data limited the analysis and conclusions, as the missing information is vital for a survival or reliability analysis.

2. **Detailed network characterization.** Analysing how the network is organized demonstrated how underground cables are concentrated in highly populated and urban areas. Additionally, this analysis showed that oil filled cables have been, over the year, replaced with dry or extruded cables. The lengths and quantities from this analysis were used for the cable failure analysis.

3. **Determining cable behaviour patterns.** It was important when analysing the failure rates to determine if they were really caused by a high number of cable incidents or if they were a result of a low cable concentration, which means that failure rates are inflated. The regions with the highest cable concentration coincided with the highest failure rates. When comparing cables types, the oil filled cables had a worse performance, which can be explained by

the fact that oil cables were older. In addition, analysis found that the worst performance voltage level was 10kV.

4. **Underground cables have a major impact on SAIDI and SAIFI QoS indicators.** There has been a general improvement in the MV underground network over the period analysed. Analysing cable's impact on the QoS indicators determined that cables increase the quality of service indicators such as SAIDI and SAIFI. The MAIFI indicator is not strongly affected by cable failures as it considers SD incidents, but the majority of cable incidents are LD, with an average duration of 161 minutes.

5. **Evidence for seasonal cable failure behaviour.** While grouping the information in months and comparing with the average temperature of the month, there seems to be a high correlation between cable failures and temperature. But when this information is analysed with daily data, the evidence is very low, despite not being totally rejected. Also in terms of dependence, the result of Hoeffding's test determined that it is very low. The hottest periods in the year, from April to July, seem to have a higher correlation, when comparing to the overall year and colder months. Maybe with more detailed and accurate data, this correlation accepted or rejected with statistical significance.

6. **Cable daily failure fitted to Weibull probability distribution.** Analysing the number of daily incidents, excluding null incident days, a distribution was fitted to the data according to the MLE method and the Kolmogorov-Smirnov goodness-of-fit test. The Weibull was determined as the best fit, despite the hypothesis for other distributions to fit the data could not be rejected. The fitted Weibull CDF can give a conditional probability of the number of cable failures for a certain day. So, knowing that there is an incident, it gives the probability that a certain number of failures will occur. This distribution can be updated every year with new cable failure information.

5.2 Future work

The objectives proposed for this thesis were achieved and can be the basis for future developments. The future work proposed:

1. **Developing a cable failure prediction model.** Based on identified cable traits and behaviour, a cable failure prediction model based on region and month could be developed.This model could be built using ANN and using historical information of cable incidents.

2. **Cable accessory study.** This thesis does analyse some cable accessory and behaviour, but not with much detail. It would be interesting to study cable accessory failures and determine if there is a relation between failure and installation type. Also it would be interesting to analyse accessory failure seasonality and fit a probability function to the failure data.

3. **Study of soil type and temperature impact on underground cable failure and developing mathematical model which describes relation.** Determine the joint soil type and the impact of temperature on underground cables, in order to determine a mathematical model which can be used to describe, based on soil type and ambient temperature, the cable's temperature. If this is achieve, another improvement could be to include the load effect.

4. **Determining the joint probability.** When and if there is sufficient statistical evidence of cable failure and temperature, a joint probability distribution could be built, in order to calculate the probability of incidents according to the temperature.

5. **Increase the data volume used in the statistical analysis in order to confirm the results obtained in the statistical analysis.** As stated in the statistical analysis, there seemed to be some statistical evidence of cable seasonal behaviour. It would be interesting to perform a similar analysis in the future in order to verify if the conclusions from the statistical analysis remain or if there are any changes.

6. **Study the impact of the variability in cable operation and cable failure.** Due to the knowledge that variable cable operation is a cable deterioration accelerating factor, it would be interesting to conduct a detailed study, acknowledging if there is a higher failure rate in regions or younger cables operated in a more variable way. Regions with renewable energy production, of any level, can be a possible focus area.

Appendix A

Annexes

A.1 Oil-filled and extruded cable ageing and deteoration tests

Table III: Diagnostic Tests for Paper/oil Insulation Cable System		
Diagnostic Test	**Advantages**	**Limitations**
Capacitance and dissipation factor	-Bulk measurement -Sensitive to moisture -*In situ*	-May not be sensitive to local degradation -Power supply limitation
Withstand test	-Picks out gross defects -*In situ*	-Can cause ageing
Gas in oil analysis	-Good indicator of type of ageing in oil and paper -*In situ* -"Condition" values proposed [9]	-Localized measurement -Need previous history to make final judgment
Other tests on oil (dielectric strength, etc.)	-Good indicator of thermal ageing -Criteria proposed for cable condition	-Localized measurements
Degree of polymerization, or burst strength of paper	-Good indicator of thermal ageing	-Destructive test
Partial Discharge (PD)	-Determines localized damage -Location possible in single runs -*In situ*	-Sensitivity limited by noise -Location not yet possible for networks
X-ray radiography	-Locate soft spots or misalignment	-Safety issues -Need to have idea of location
Visual Inspection	-Leaks, cracks, corrosion -Mechanical misalignment	-Not all system visible
Teardown	-Can show evidence of thermal ageing, wrinkles tracking, waxing, discoloration, etc.	-Destructive test

Figure A.1: 1Diagnostic tests for paper/oil insulated cable systems [17]

Table IV: Diagnostic Tests for Wet or Dry Extruded Cable Systems					
Electrical Tests					
Destructive	**Comments**	***In Situ***	**Critical Value**	**Advantages**	**Limitations**
AC Breakdown		No	≥ 10 kV/mm	-Simple test	-Many samples needed
Impulse BD		No		-Simple test	-Many samples needed
Non-Destructive	Comments	*In Situ*	Critical Value		
DC/AC Withstand or maintenance	60 Hz, 0.1 Hz	Yes	2.5 to $3U_0$ for 15 min	-Simple test	-Could cause damage
Oscillating Wave		Yes	Needed	-Simulates surge	-Equipment needed -Could cause damage
Dielectric Spectroscopy	10^{-3} - 10^{+2} Hz	Yes	Needed	-Test at or below operating voltage	-Stray currents a possible problem
Capacitance Tan Delta	60 Hz, 0.1 Hz	Yes	Needed	-Test at or below operating voltage	-Power Supply needed for 60 Hz - Stray currents a possible problem
AC Current Waveform	60 Hz, 0.1 Hz	Yes	Needed	-Test at or below operating voltage	-Power Supply needed for 60 Hz - Stray currents a possible problem
DC Leakage Current/ Residual/Recovery voltage	Low DC voltages applied	Yes	Needed	-Test at or below operating voltage	- Stray currents a possible problem
Partial Discharge	60 Hz, 0.1 Hz	Yes	Needed	-Related to final breakdown mechanism	-Needs PD free source -Interference affects sensitivity
Space Charge	Pressure Pulse, TSC	No		-Useful research tool	-Cannot be used on cables -AC measurements difficult
Electroluminescence	Related to space charge motion	No		-Useful research tool	-Cannot be used on cables
Non-Electrical Tests					
Non-Destructive	**Comments**			**Advantages**	**Limitations**
Polymer Morphology	DSC, SAXS, etc.			-Useful research tool -DSC gives thermal history	-Effect on ageing?
Optical Microscopy	Tree length and density			-Gives tree characteristics -Gives contaminant level -Can see roughness of shields	-Tedious measurements unless automated
Impurity Analysis	EDX, WDX, PIXE, NAA			-Analysis of single trees	-Expensive equipment -Dedicated operator needed
Chemical Analysis	IR, FTIR, XPS UV, etc.			-Sensitive to ageing -Analyze contaminants	-Localized measurement -Expensive equipment
Visual Inspection (Installation or failed sample)	Shields and concentric neutral Tree counts			-See condition of neutrals -See condition of insulation shield -Check integrity of accessories	-

Figure A.2: Ageing factors that affect cable insulation systems [17]

A.2 Distribution fitting

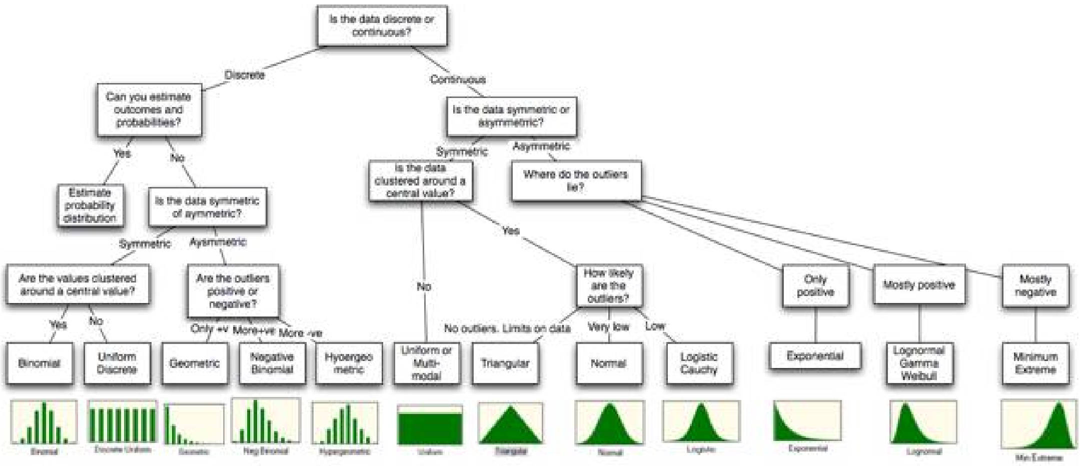


Figure A.3: Distributional choices [18]

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